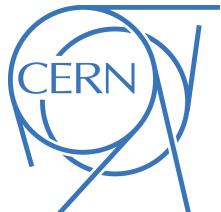


Open heavy-flavour production with ALICE at the LHC

Jaime Norman (University of Liverpool, UK)
On behalf of the ALICE collaboration



High p_T Physics in the RHIC-LHC Era Workshop
April 12-15, 2016, Brookhaven National Laboratory



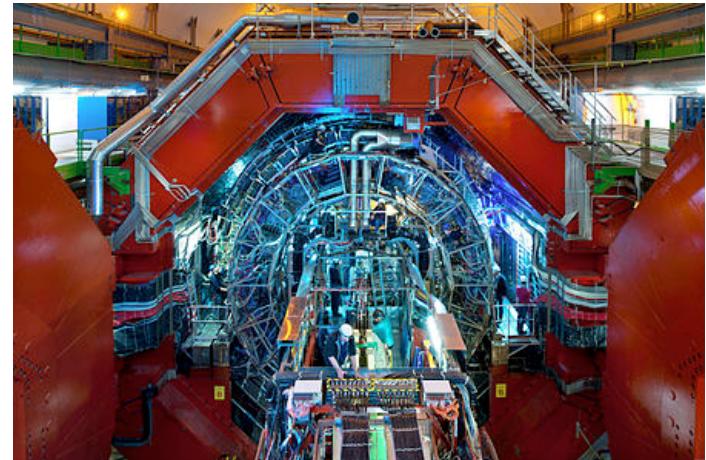
Science & Technology
Facilities Council





Outline

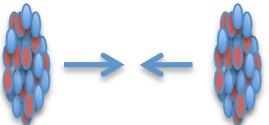
- Why heavy flavours?
- Observables
 - Nuclear modification factor
 - Elliptic flow
- The ALICE detector and heavy-flavour reconstruction
- Results
 - pp collisions
 - p-Pb collisions
 - Pb-Pb collisions
- Summary and outlook





Why heavy flavours?

Pb-Pb
collisions



Heavy quarks (c,b)

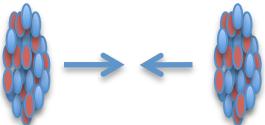
- Short formation time
- $m_{c,b} \gg \Lambda_{QCD}$
- Produced in the early stages of the collision and see full space-time evolution of collision system

Heavy quarks offer unique way to study properties of strongly-interacting medium created in Pb-Pb collisions at the LHC



Why heavy flavours?

Pb-Pb collisions

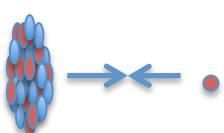


Heavy quarks (c,b)

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Heavy quarks offer unique way to study properties of strongly-interacting medium created in Pb-Pb collisions at the LHC

p-Pb collisions



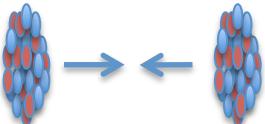
Smaller collision system helps disentangle hot/cold nuclear matter effects

- Modification of the PDFs in nuclei
- k_T broadening
- Final-state effects



Why heavy flavours?

Pb-Pb collisions

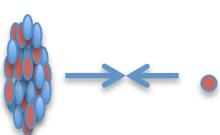


Heavy quarks (c,b)

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p-Pb collisions



Smaller collision system helps disentangle hot/cold nuclear matter effects

- Modification of the PDFs in nuclei
- k_T broadening
- Final-state effects

pp collisions



pp collisions

- Reference for p-Pb/Pb-Pb measurements
- Test of pQCD predictions/ production mechanisms
 - Role of multi-parton interactions (MPIs)



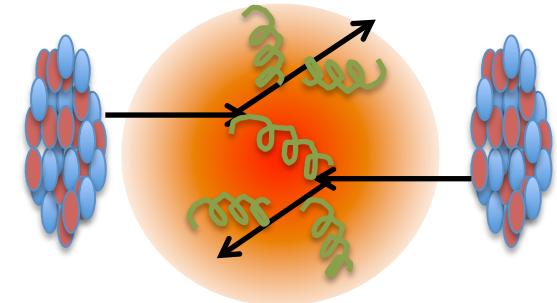
Heavy-quark energy loss

Abundance of particles relative to pp collisions quantified by the **nuclear modification factor**:

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

In medium energy loss via radiative and collisional processes, dependent on:

- Color charge



e.g BDMPS formalism

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q} L^2}{\omega}}$$

$C_R = 4/3$ for quarks, 3 for gluons

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291.

Zakharov, JTEPL 63 (1996) 952.

Salgado, Wiedemann, PRD 68(2003) 0140



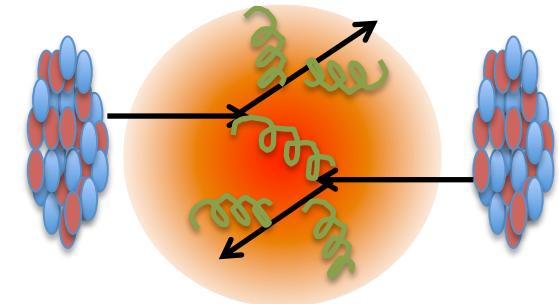
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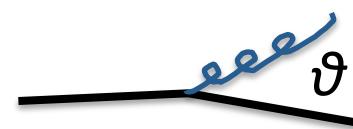
In medium energy loss via radiative and collisional processes, dependent on:

- Color charge
- Mass dependent suppression due to screening of gluon emission at forward angles (**dead-cone effect**)



Gluon radiation suppressed at

$$\theta < m_Q / E_Q$$



Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291.

Zakharov, JTEPL 63 (1996) 952.

Salgado, Wiedemann, PRD 68(2003) 0140

Dokshitzer and Kharzeev, PLB 519 (2001) 199



Heavy-quark energy loss

Abundance of particles relative to pp collisions quantified by the **nuclear modification factor**:

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

In medium energy loss via radiative and collisional processes, dependent on:

- Color charge
- Mass dependent suppression due to screening of gluon emission at forward angles (**dead-cone effect**)

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \quad \rightarrow \quad R_{AA}^\pi < R_{AA}^D < R_{AA}^B$$

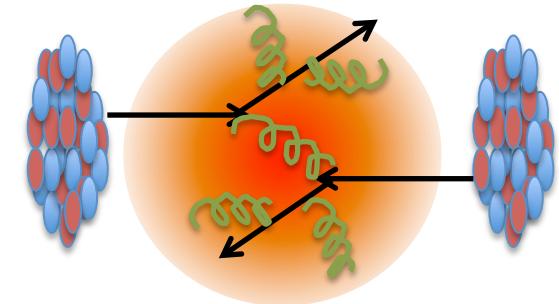
?

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291.

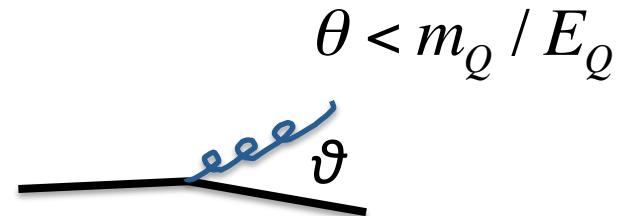
Zakharov, JTEPL 63 (1996) 952.

Salgado, Wiedemann, PRD 68(2003) 0140

Dokshitzer and Kharzeev, PLB 519 (2001) 199



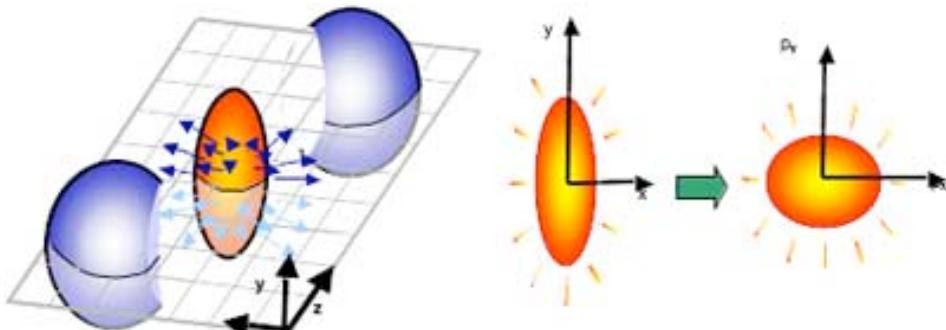
Gluon radiation suppressed at





Azimuthal anisotropy

Initial geometrical anisotropy → final-state momentum anisotropy



Quantified by 2nd coefficient in Fourier expansion of momentum distribution in φ :

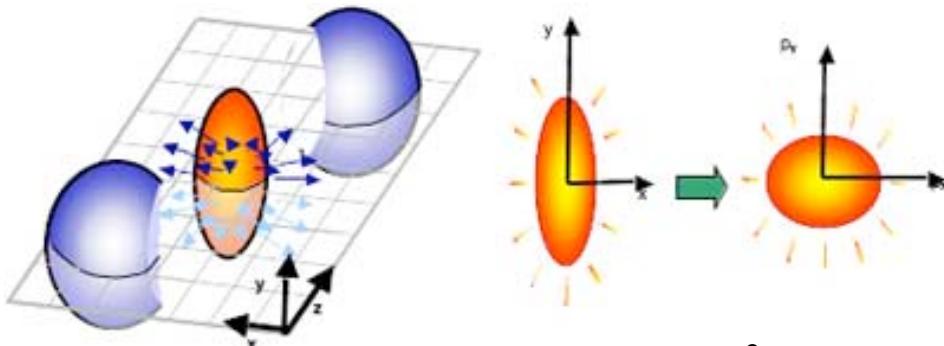
$$\frac{d^2N}{d\varphi dp_T} = \frac{dN}{2\pi dp_T} \left[1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos n(\varphi - \Psi_n) \right]$$

$$\rightarrow v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$



Azimuthal anisotropy

Initial geometrical anisotropy → final-state momentum anisotropy



Quantified by 2nd coefficient in Fourier expansion of momentum distribution in φ :

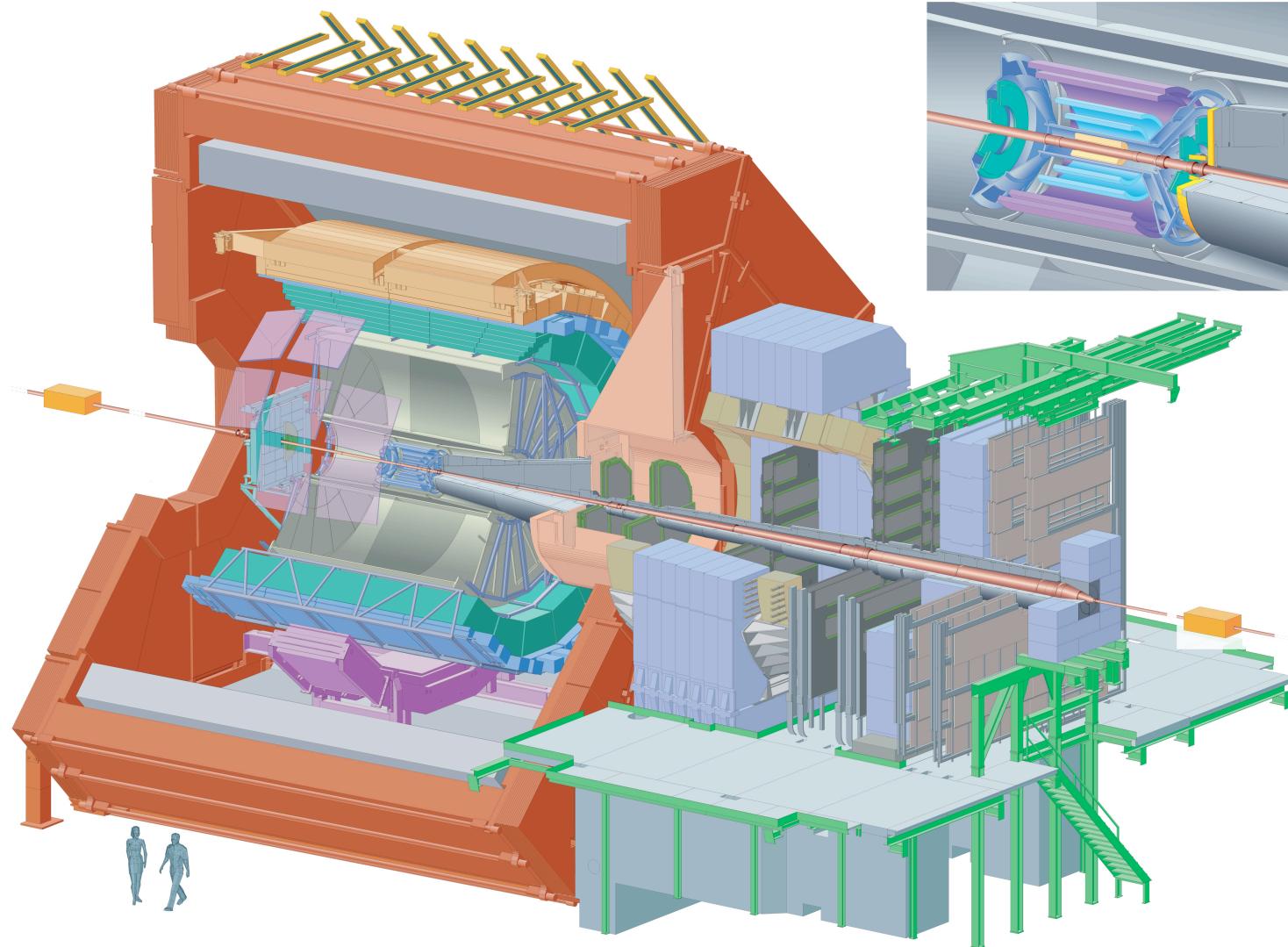
$$\frac{d^2N}{d\varphi dp_T} = \frac{dN}{2\pi dp_T} \left[1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos n(\varphi - \Psi_n) \right]$$

$$\rightarrow v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

- **2nd coefficient v_2 probes:**
 - Heavy-quark participation in thermalisation and collective hydrodynamical expansion at low p_T
 - Path-length dependent energy loss at high p_T ($> 8\text{-}10 \text{ GeV}/c$)

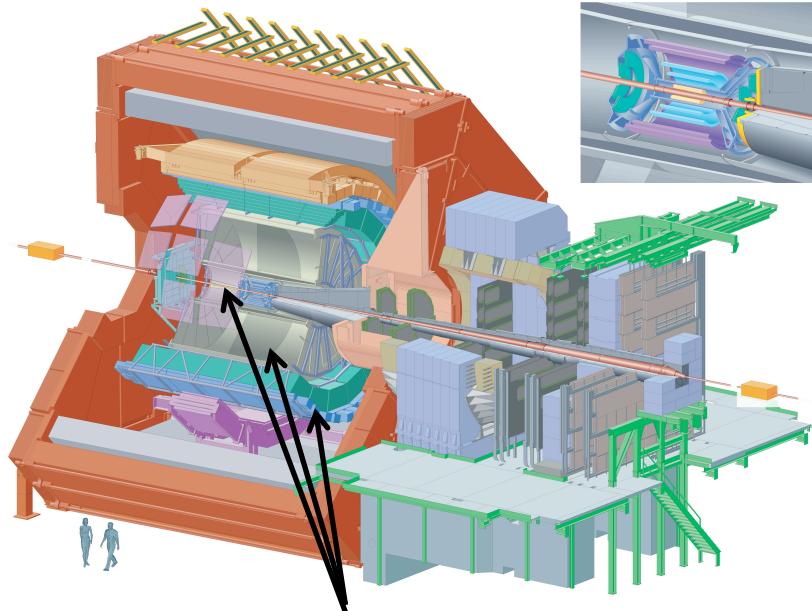


A Large Ion Collider Experiment





ALICE – D mesons → hadrons



Inner tracking system (ITS)
Time projection chamber (TPC)
Time of flight detector (TOF):
Tracking, PID
 $|\eta| < 0.8$

Study heavy flavours via:

- **Fully reconstructed D mesons (D^0 , D^+ , D^{*+} , D_s)**

Analysis performed via:

- **Cuts on decay topologies** exploiting decay vertex displacement from primary vertex
- **PID** using TPC via dE/dx and TOF via time of flight measurement
- **Signal extraction** via invariant mass distribution
- **Feed-down subtracted** from pQCD prediction of D from b/c

$D^0 \rightarrow K^- \pi^+$	$\text{ct} \sim 123 \mu\text{m}$	$\text{BR} \sim 3.88\%$
$D^+ \rightarrow K^- \pi^+ \pi^+$	$\text{ct} \sim 312 \mu\text{m}$	$\text{BR} \sim 9.13\%$
$D^{*+} \rightarrow D^0 \pi^+$	-	$\text{BR} \sim 67.7\%$
$D_s^+ \rightarrow \phi \pi^+ (K^- K^+ \pi^+)$	$\text{ct} \sim 150 \mu\text{m}$	$\text{BR} \sim 2.28\%$

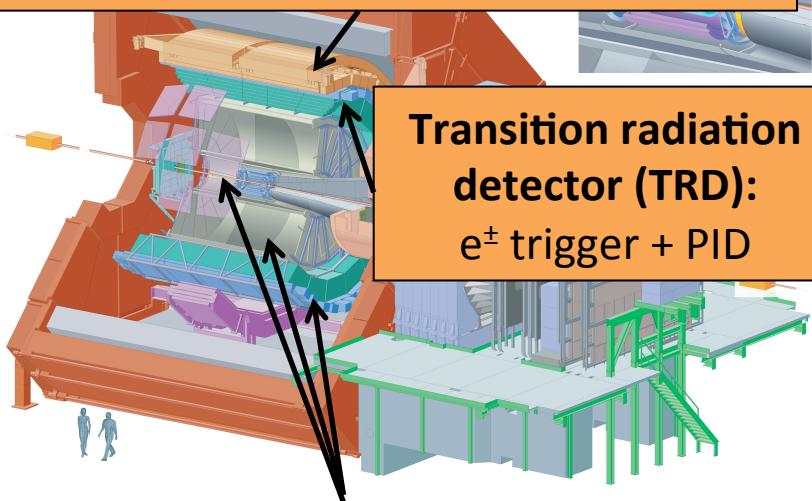


ALICE – heavy-flavour decay electrons



Electromagnetic calorimeter (EMCal):

e^\pm trigger + PID



Transition radiation detector (TRD):

e^\pm trigger + PID

Inner tracking system (ITS)

Time projection chamber (TPC)

Time of flight detector (TOF):

Tracking, PID

$|\eta| < 0.8$

Study heavy flavours via:

- **Fully reconstructed D mesons (D^0 , D^+ , D^{*+} , D_s)**
- **Semi-electronic HF decays**

Background contributions subtracted from inclusive electron spectra:

- Direct and decay γ conversions
- π and η Dalitz decays
- Quarkonia dielectron decays
- Semileptonic kaon decays
- High p_T W decays

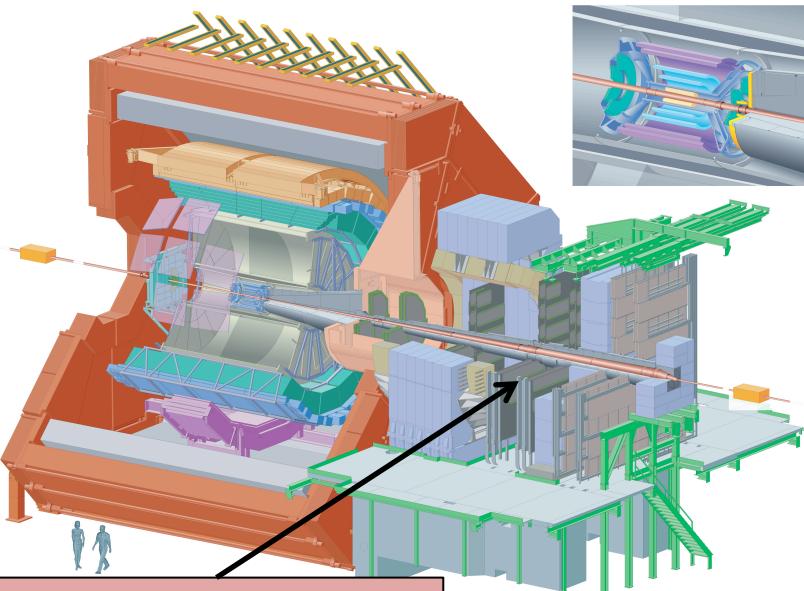
Background subtracted via:

- **Cocktail method** based on measured particle spectra where possible
- **Invariant mass method** (like sign – unlike sign electron pairs)

Also possible to separate heavy-flavour electrons from beauty via impact parameter distribution



ALICE – heavy-flavour decay muons



Forward muon arm:
Tracking + trigger
 $-2.5 > \eta > -4.0$

Study heavy flavours via:

- **Fully reconstructed D mesons (D^0 , D^+ , D^{*+} , D_s)**
- **Semi-electronic HF decays**
- **Semi-muonic HF decays**

Analysis performed via:

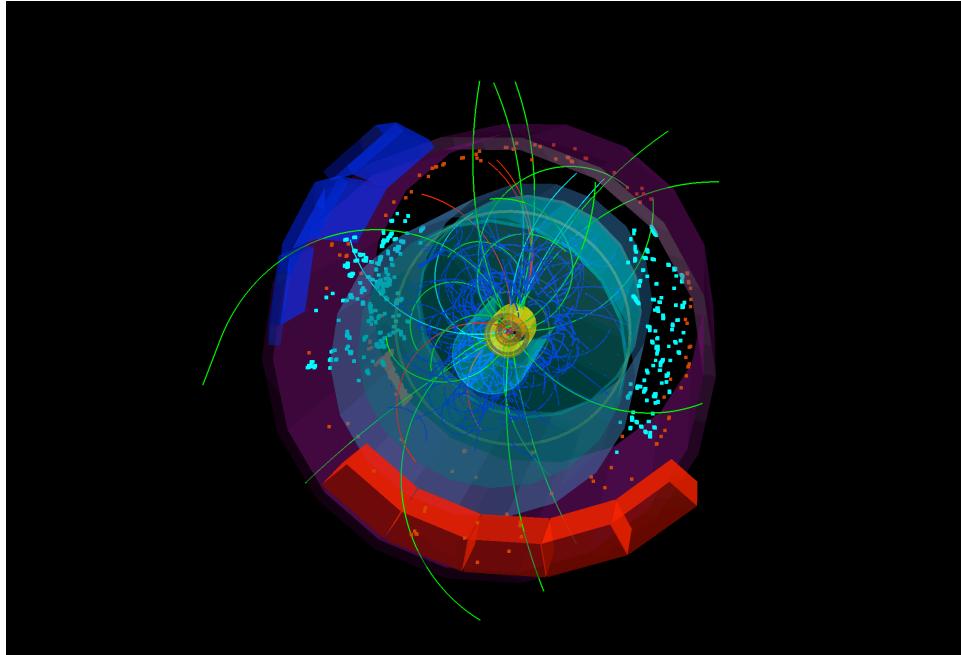
- **Acceptance and geometrical cuts**
- **Muon tracking/trigger matching to reject hadrons**
- **Distance of closest approach cut to remove tracks from beam-gas interactions**

Background subtracted from $\mu^\pm \leftarrow b, c$, via:

- Primary π , K decays estimated via data –tuned MC cocktail (Pb-Pb/p-Pb collisions) or MC (pp collisions)
- High p_T background from W decays estimated via MC



pp collisions

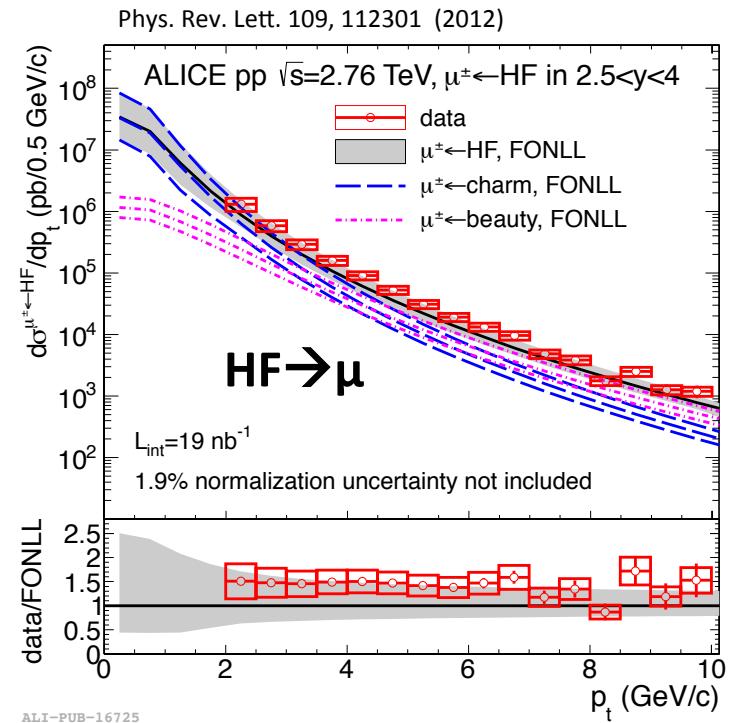
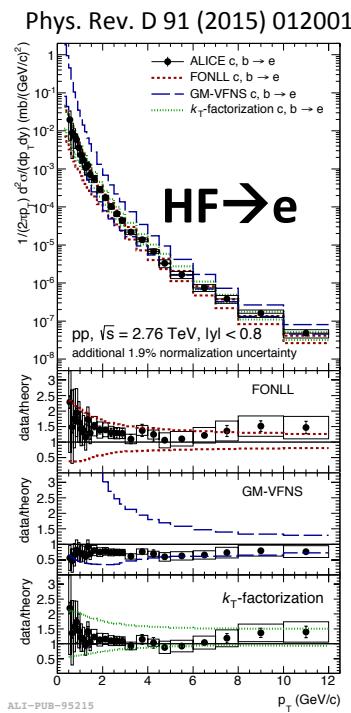
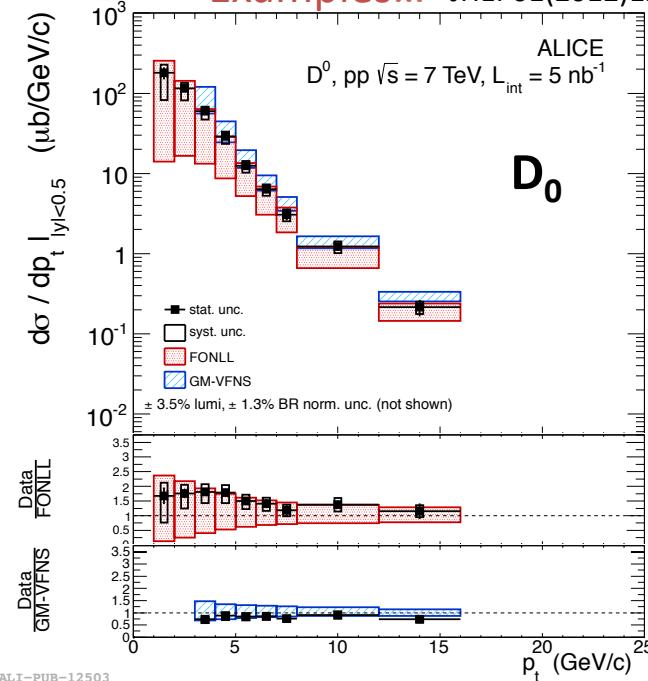


$\sqrt{s} = 2.76 \text{ TeV}, 7 \text{ TeV}$

p_T -differential cross sections



Examples... JHEP01(2012)128

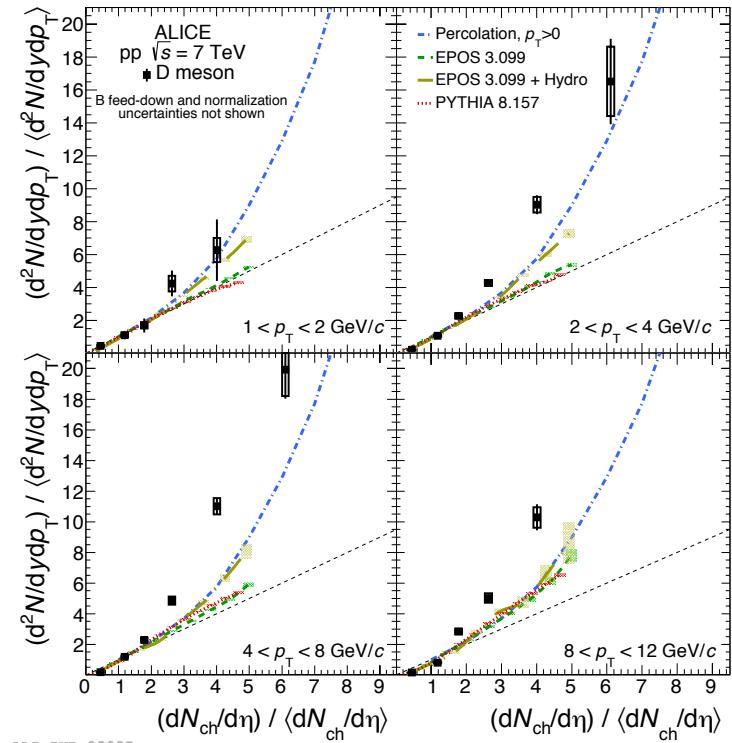
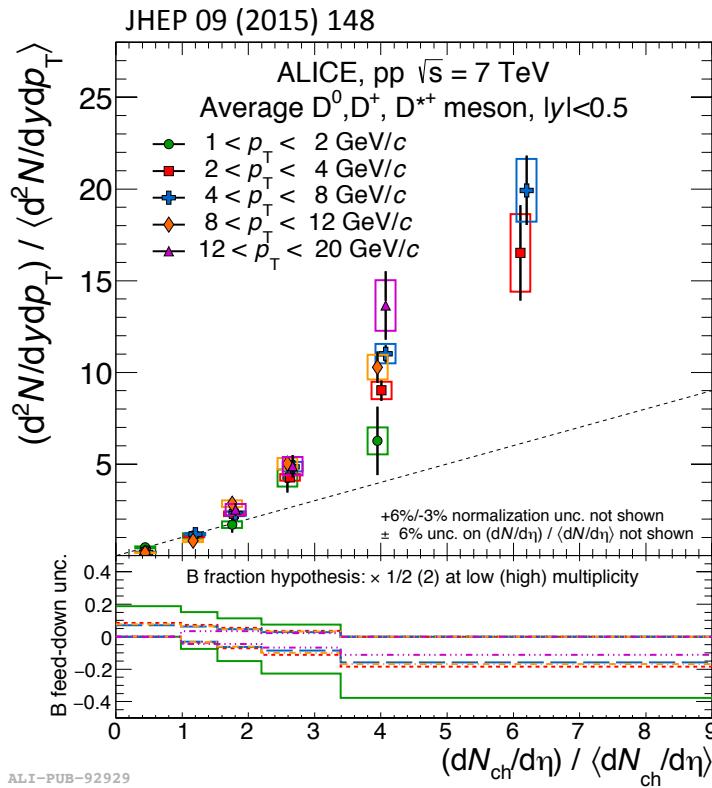


- p_T differential cross section measured for D^0 , D^+ , D^* , D_s , heavy-flavour decay muons, heavy-flavour decay electrons + beauty decay electrons at $\sqrt{s} = 7$ TeV, $\sqrt{s} = 2.76$ TeV
- Described by pQCD calculations within uncertainties

FONLL: JHEP05(1998) 007; JHEP0103(2001) 006; JHEP1210(2012) 137;
CERN-PH-TH/2011-227; JHEP05, 007 (1998)
 k_T -factorisation Phys. Rev.D87 (2013) 094022

GM-VFNS: Phys. Rev. Lett. 96(2006) 012001; Eur. Phys. J. C72 (2012) 2082; Nucl. Phys. B872 no. 2, (2013) 253-264;
Nucl. Phys. B876 no. 1, (2013) 334-337; Phys. Rev. D71 (2005) 014018; Eur. Phys. J. C41 (2005) 199-212,

D-meson yield vs $dN_{\text{ch}}/\text{d}\eta$

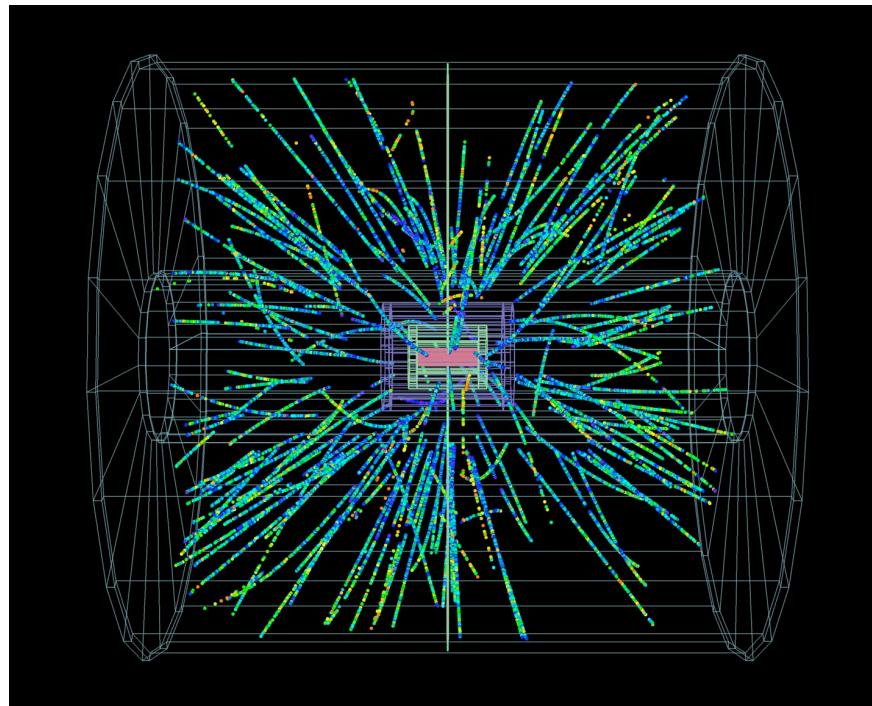


Self-normalised yield as a function of $dN_{\text{ch}}/\text{d}\eta$ in pp collisions **increases steeper than linearly**

- Models including MPIs + hydrodynamical effects can qualitatively reproduce the observed trend

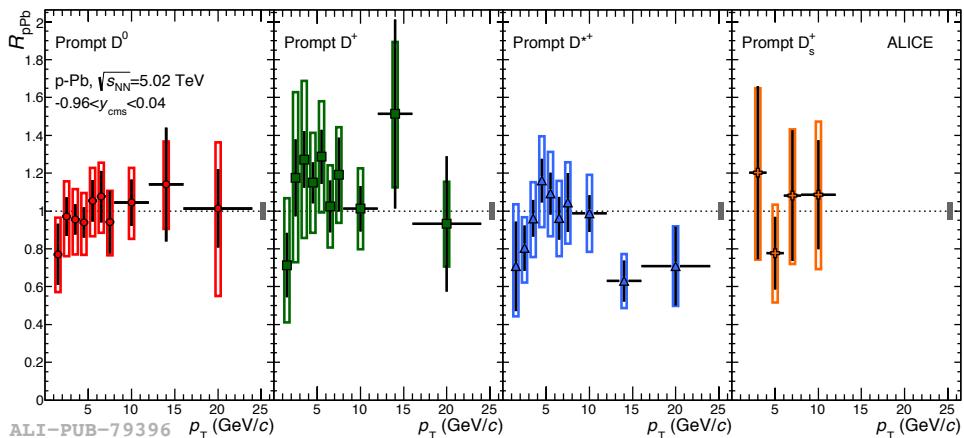


p-Pb collisions



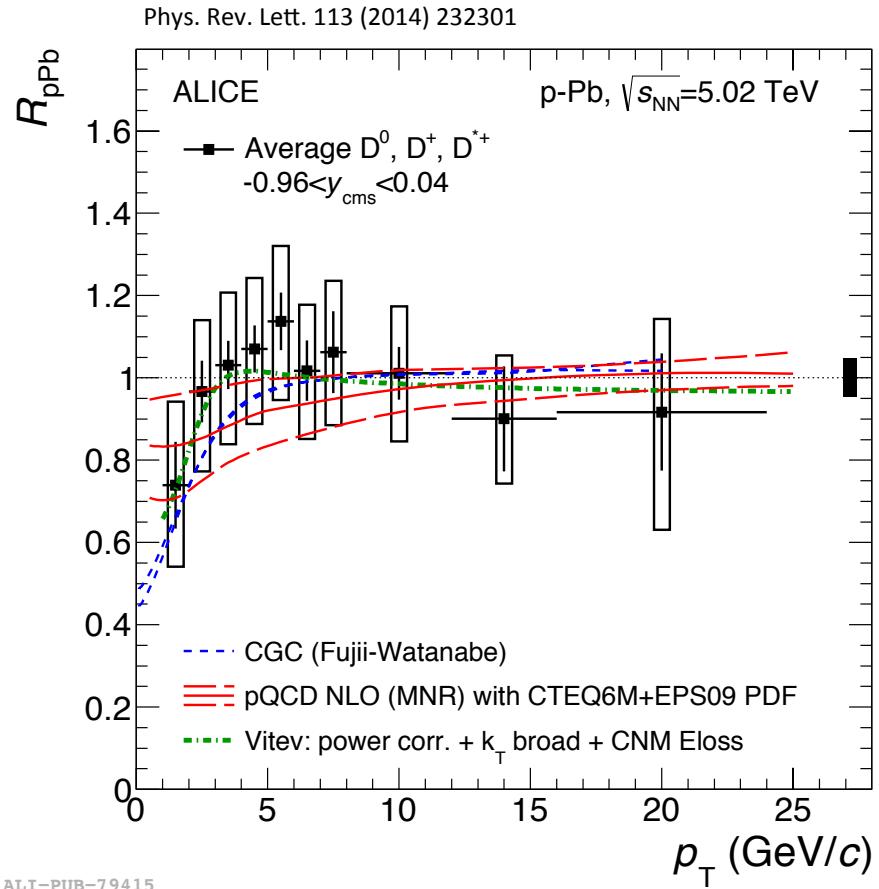
$\sqrt{s_{NN}} = 5.02 \text{ TeV}$

D-meson R_{pPb}



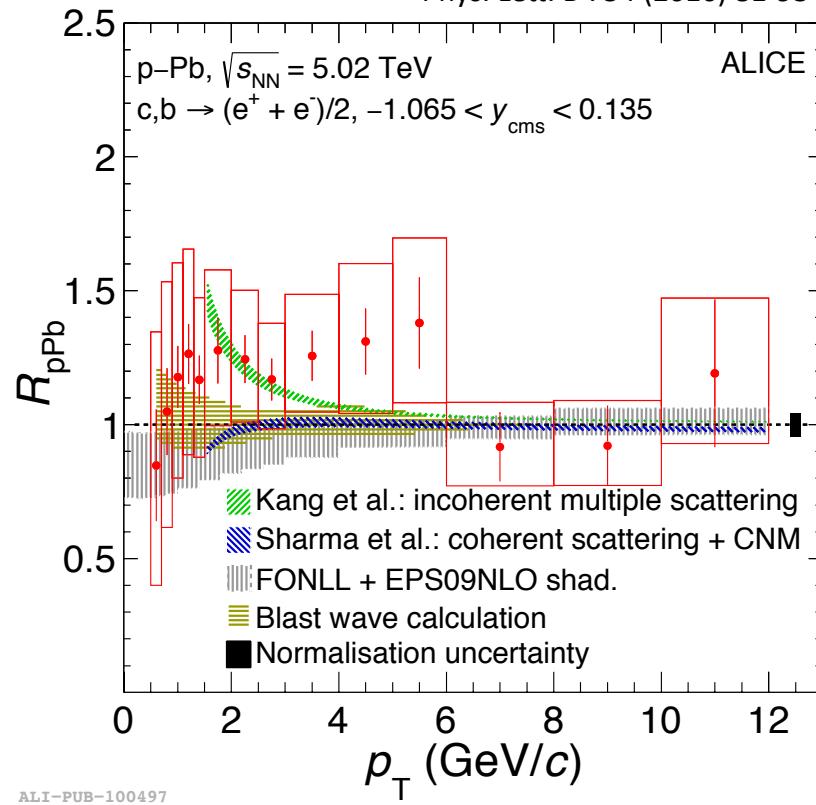
$$R_{\text{pPb}}(p_{\text{T}}) = \frac{1}{A} \frac{d\sigma_{\text{pPb}} / dp_{\text{T}}}{d\sigma_{\text{pp}} / dp_{\text{T}}}$$

- D-meson R_{pPb} mostly **consistent with unity** for all D-meson species
- Compatible with models which include initial-state effects
 - **pQCD NLO (MNR)**: Nucl. Phys. B 373 (1992) 295, JHEP 04 (2009) 065, JHEP 0310 (2003) 046, **CGC**: arXiv:1308.1258, **Vitev**: Phys. Rev. C 80 (2009) 054902





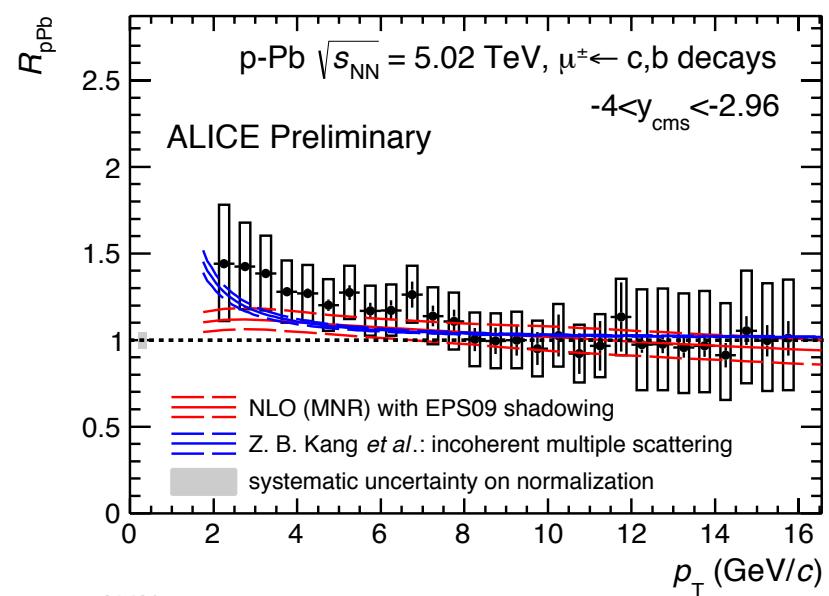
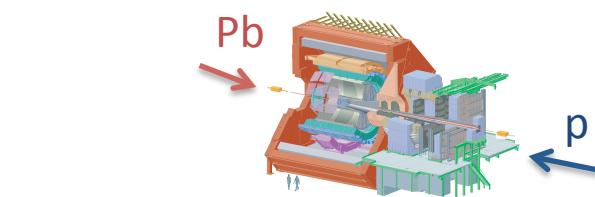
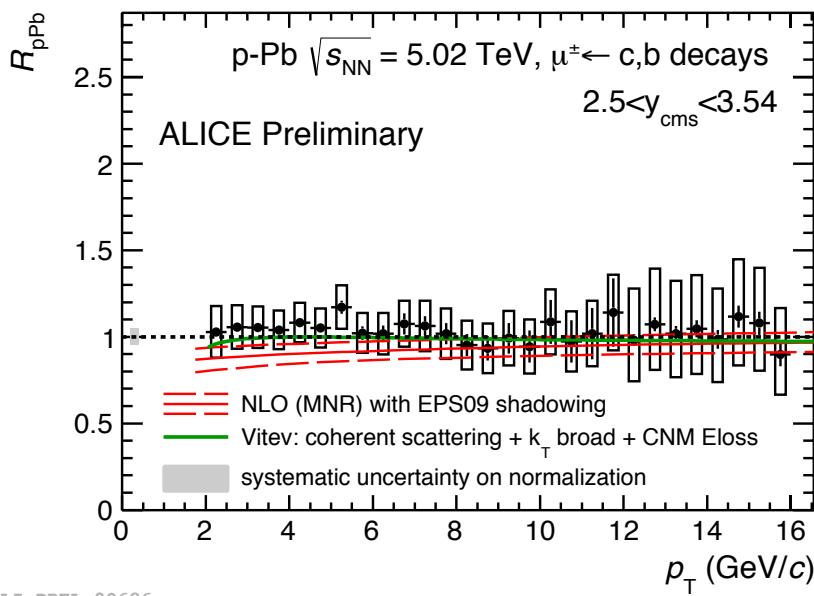
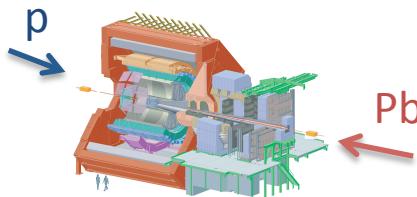
Phys. Lett. B 754 (2016) 81-93



- p_{T} -differential cross section measured for inclusive electrons from heavy-flavour decays, in $0.5 < p_{\text{T}} < 12 \text{ GeV}/c$
- R_{pPb} **consistent with unity**
- Compatible with models that include initial-state effects

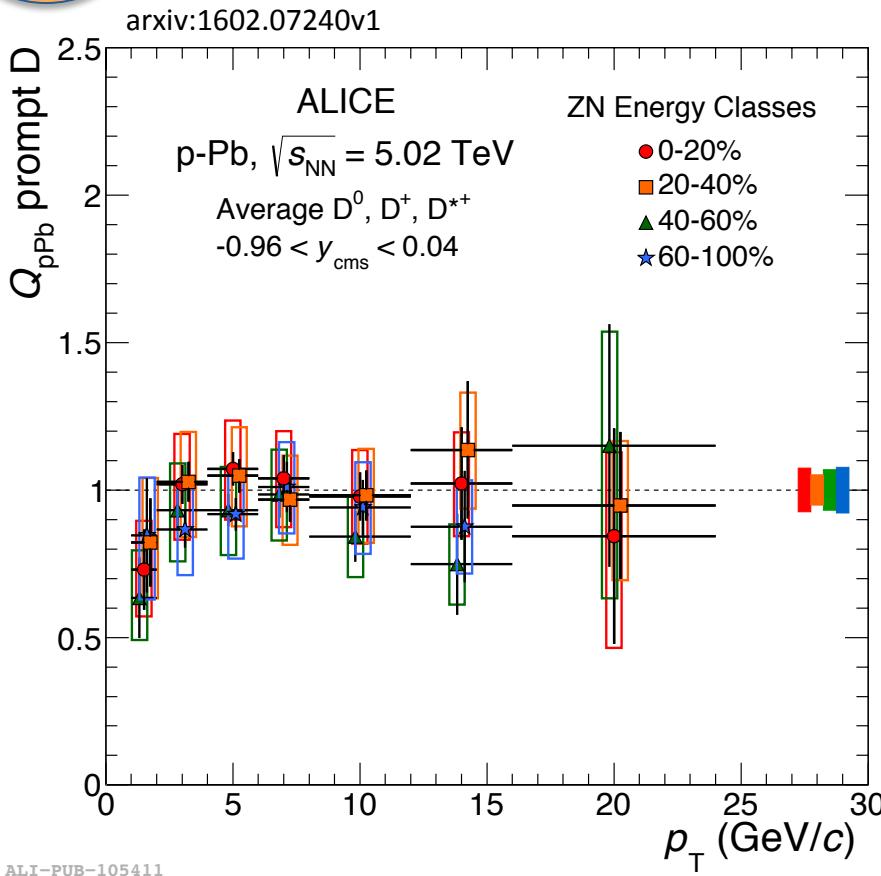
Kang et al.: PLB 740 (2015) 23 ; Sharma et al.: Phys. Rev. C80 (2009) 054902; FONLL M. Cacciari et al., JHEP 9805 (1998) 007; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065;

p-Pb Heavy-flavour decay muon R_{pPb}



R_{pPb} of heavy-flavour decay muons described by calculations including cold nuclear matter effects, in both forward (p-going) and backward (Pb-going) rapidity regions

D-meson Q_{pPb}



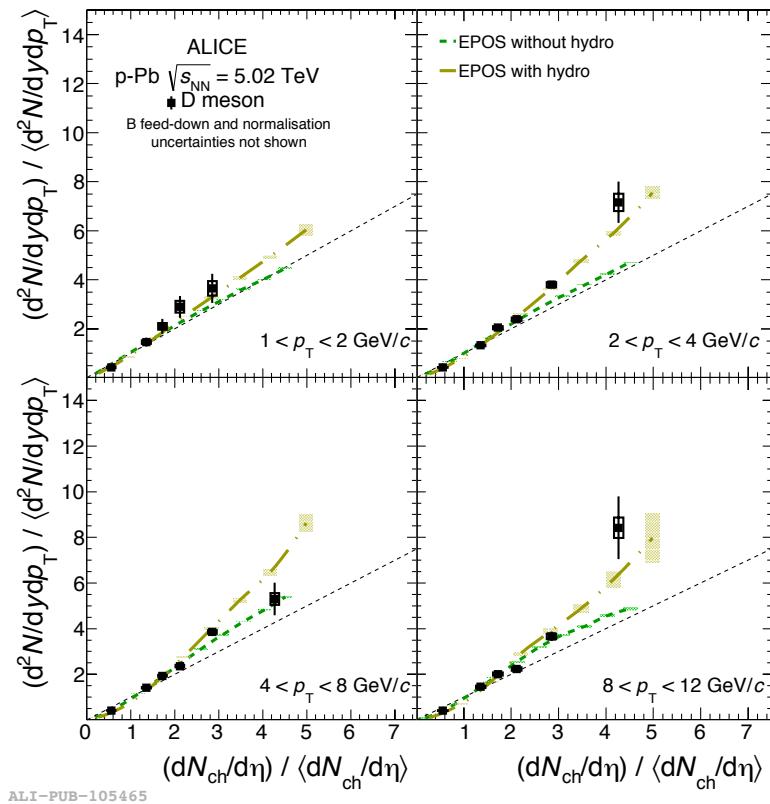
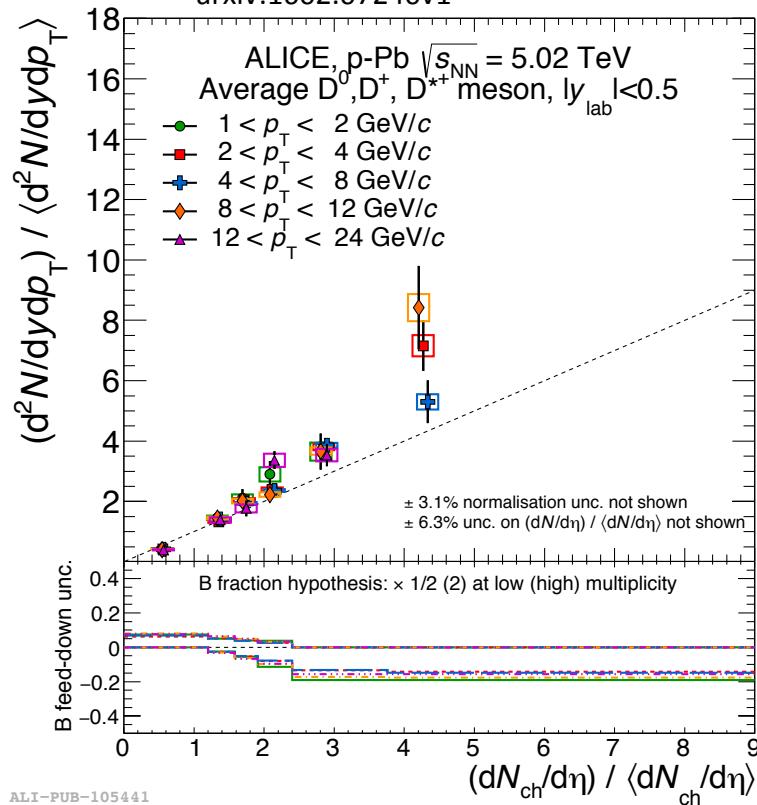
$$Q_{\text{pPb}}^{\text{mult}}(p_T) = \frac{1}{\langle T_{\text{pPb}}^{\text{mult}} \rangle} \frac{dN_{\text{pPb}} / dp_T}{d\sigma_{\text{pp}} / dp_T}$$

- Q_{pPb} equivalent to R_{pPb} measured in different multiplicity (centrality) intervals
- Centrality determined using Zero-Degree Neutron Calorimeter (ZN)
- **No centrality dependence seen in the suppression of D mesons**

D-meson yield vs $dN_{\text{ch}}/\langle dN_{\text{ch}} \rangle$



arxiv:1602.07240v1



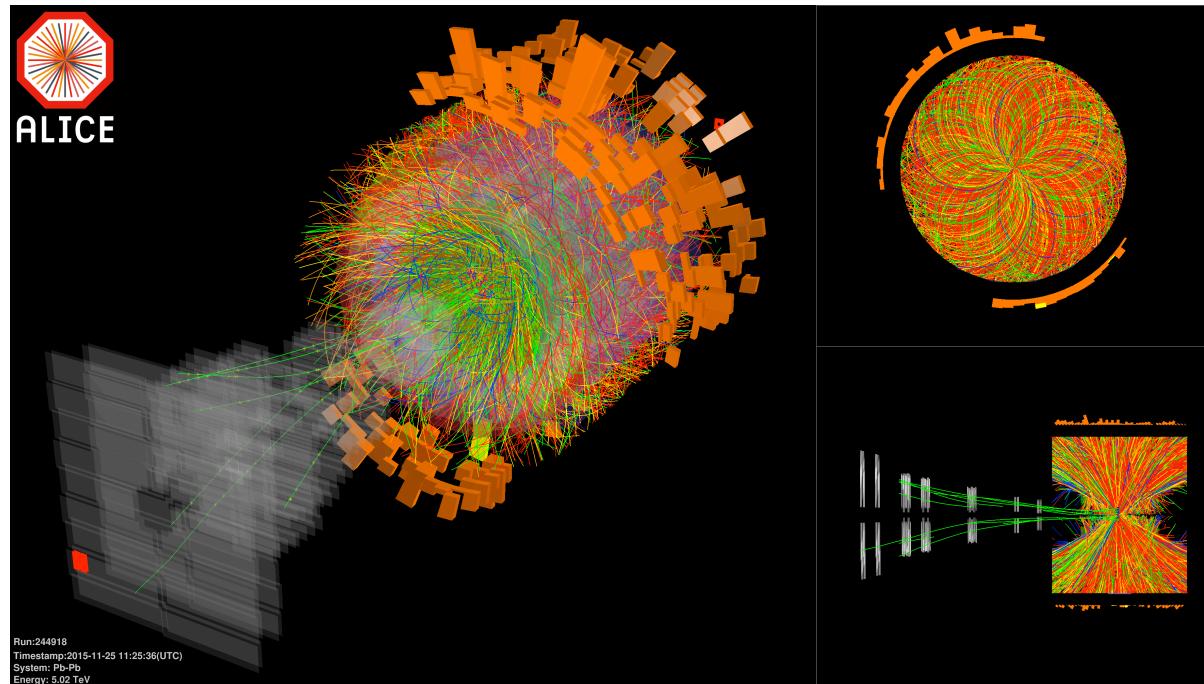
Self-normalised yield as a function $dN_{\text{ch}}/\langle dN_{\text{ch}} \rangle$ in p-Pb collisions **increases steeper than linearly**

- Reproduced by model including hydrodynamic flow

EPOS3: Phys.Rept. 350 (2001) 93–289;
 Phys.Rev.C89 (2014) 064903

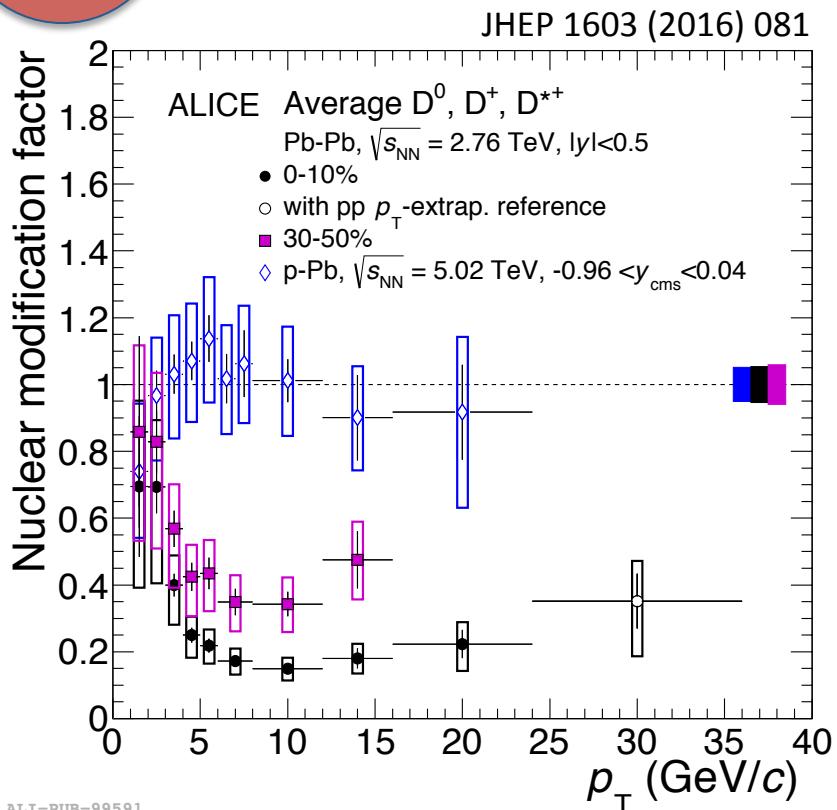


Pb-Pb collisions



$$\sqrt{s_{NN}} = 2.76 \text{ TeV}$$

D-meson R_{AA}



ALI-PUB-99591

Strong suppression of D mesons seen in Pb-Pb collisions:

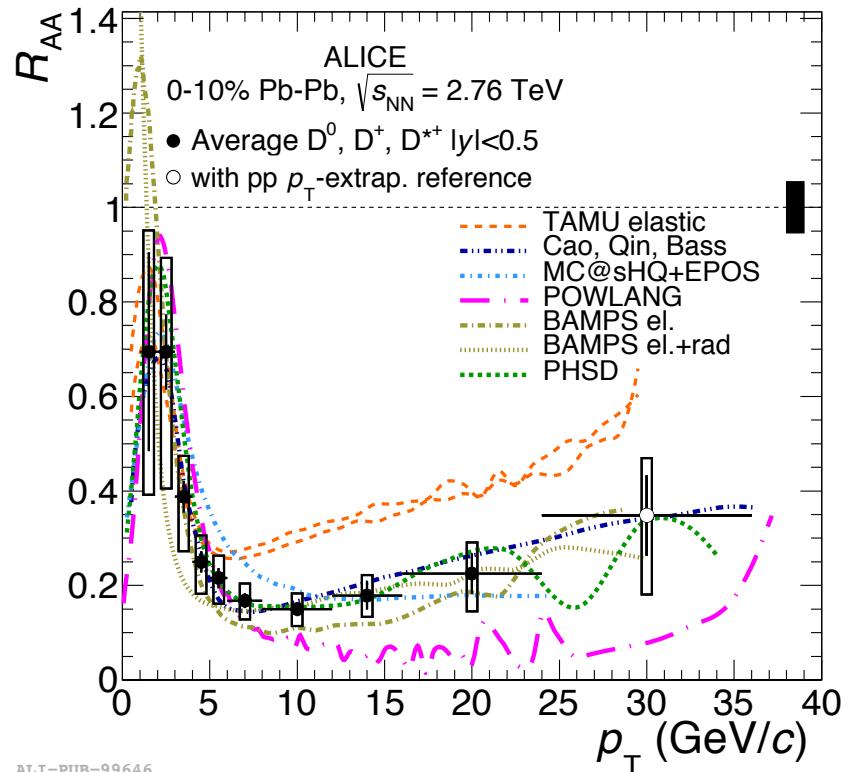
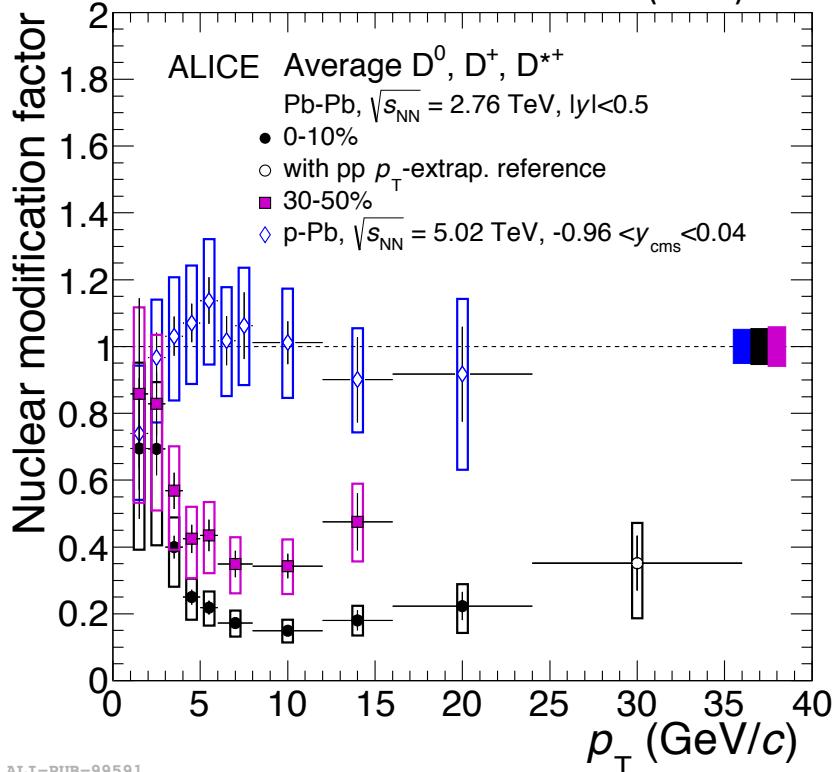
- **Suppression not due to cold matter effects ($R_{p\text{Pb}}$ at high p_T consistent with unity)**

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

D-meson R_{AA}



JHEP 1603 (2016) 081



Strong suppression of D mesons seen in Pb-Pb collisions:

- **Suppression not due to cold matter effects ($R_{p\text{p}b}$ at high p_T consistent with unity)**
- Described well by models which include collisional and radiative energy loss

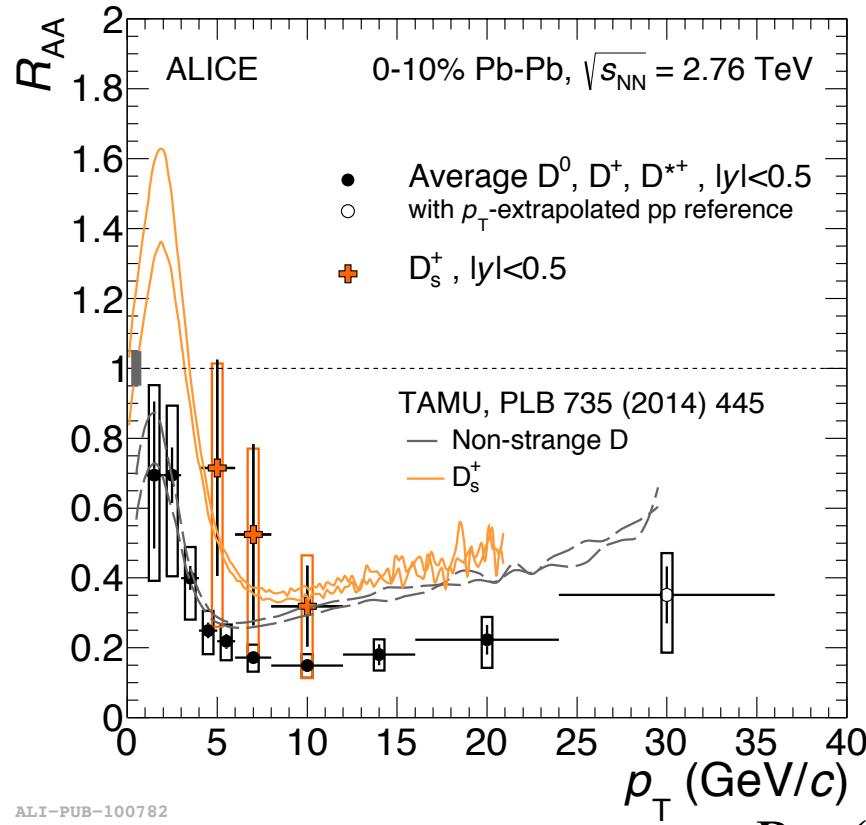
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

TAMU: arXiv:1401.3817;; MC@sHQ +EPOS: PRC 89 (2014) 014905;; POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; BAMPS: PLB 717 (2012) 430;
arXiv:1310.3597v1[hep-ph]; Cao,Quin, Bass: PRC 88 (2013);



D-meson R_{AA}

JHEP 1603 (2016) 082



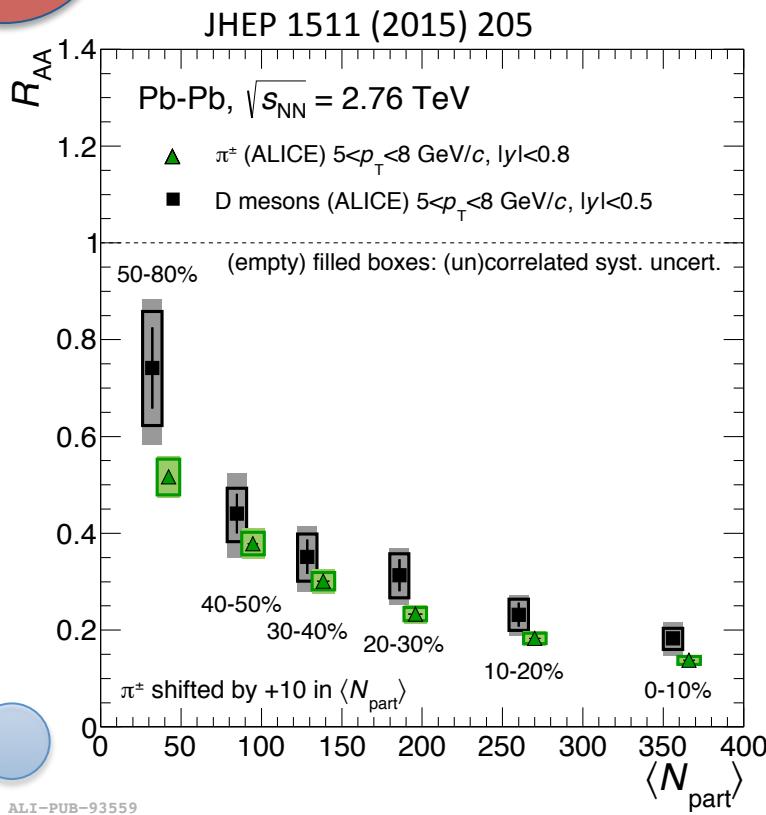
Less suppression of D_s mesons?:

- Expected if recombination has a role to play in hadronisation

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}$$

TAMU: Phys. Rev. C86 (2012) 014903, Phys. Lett. B 735 (2014) 445–450

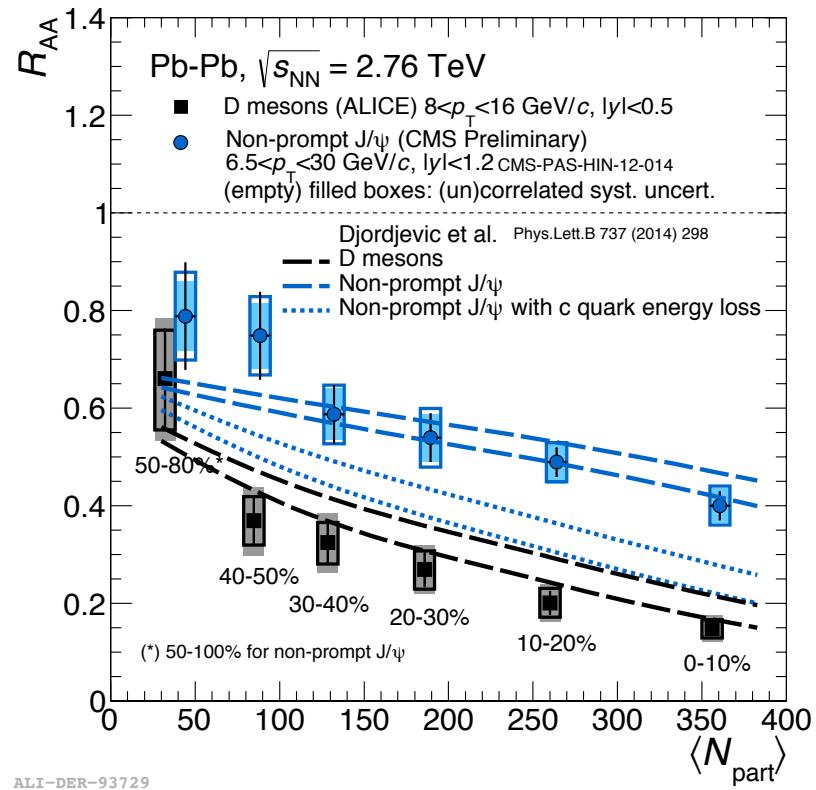
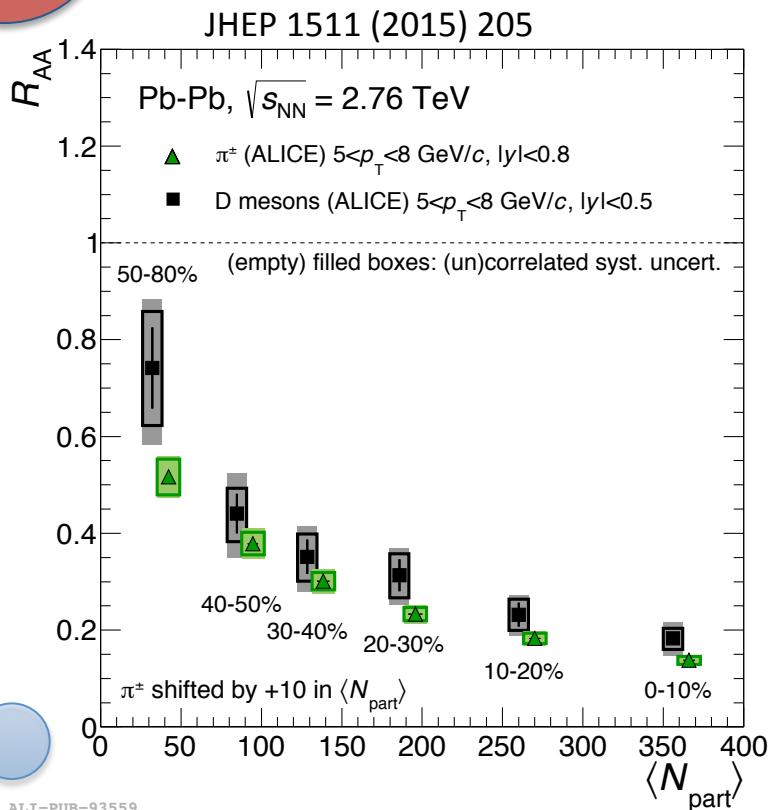
D-meson R_{AA} vs centrality



At **high p_T** : $R_{AA}(\pi) \approx R_{AA}(D)$

- R_{AA} of charged particles **compatible** with that of D mesons (within current uncertainties)

D-meson R_{AA} vs centrality



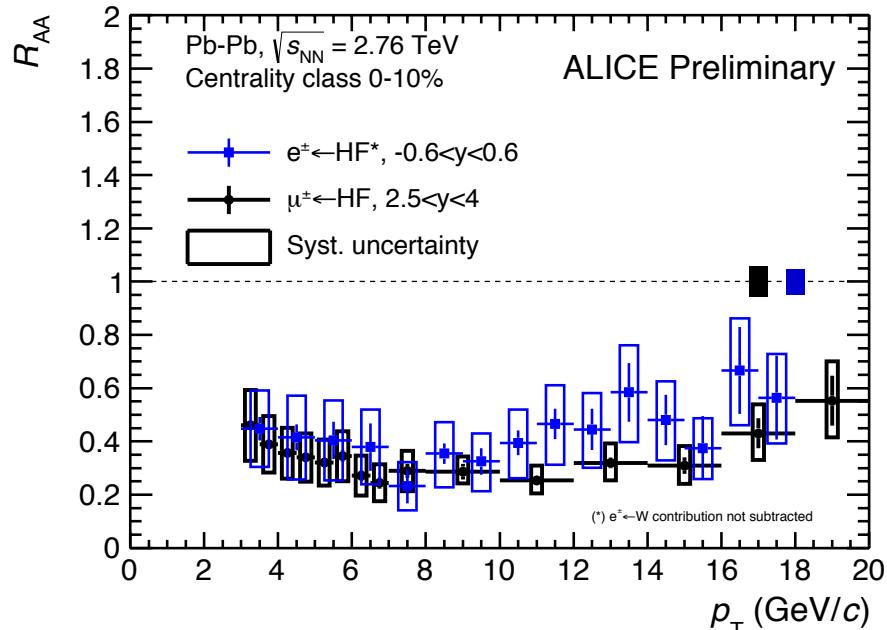
At high p_T : $R_{AA}(\pi) \approx R_{AA}(D)$

- R_{AA} of charged particles **compatible** with that of D mesons (within current uncertainties)
- R_{AA} of non-prompt J/ ψ (from B) measured by CMS **higher** than that of D mesons
 - **Consistent with mass-dependent energy loss picture**

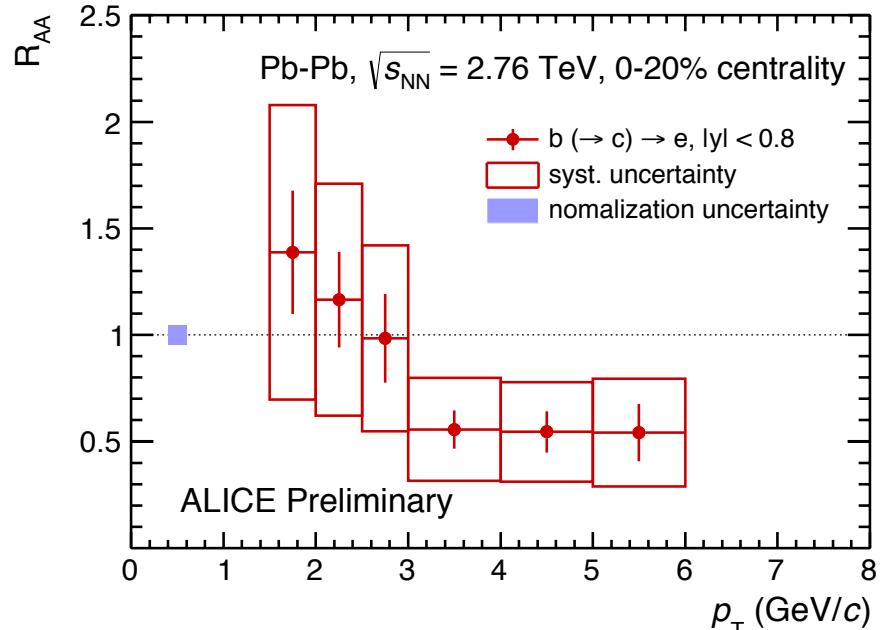
$$R_{AA}(D) > R_{AA}(B)$$

Djordjevic et al.: Phys.Lett. B737 (2014) 298–302

Heavy-flavour decay lepton R_{AA}



ALI-PREL-101085



ALI-PREL-74678

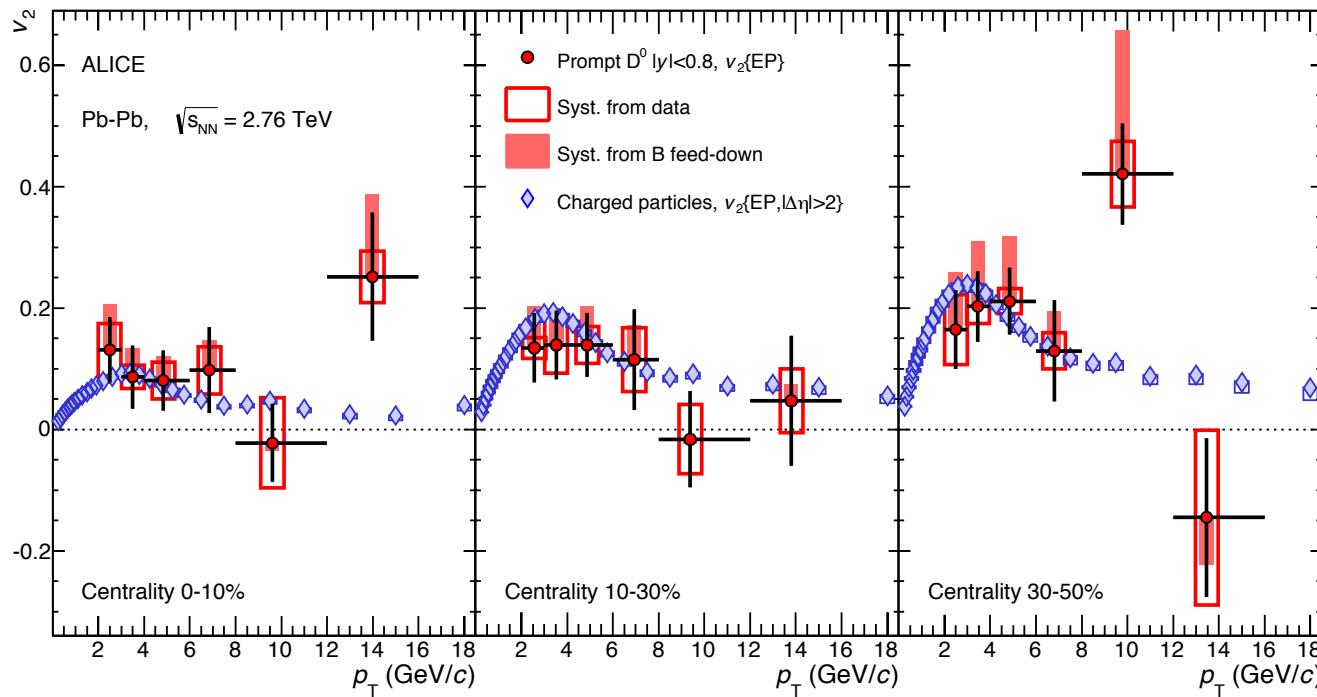
- Strong heavy-flavour decay electron and muon suppression
- Heavy-flavour decay lepton suppression at mid rapidity and forward rapidity compatible within uncertainties**

- Electrons from **beauty decays** extracted using global fit to impact parameter distribution
- Hint of suppression at high p_T** (with large uncertainties at present)

D-meson v_2



Phys. Rev. Lett. 111 (2013) 102301

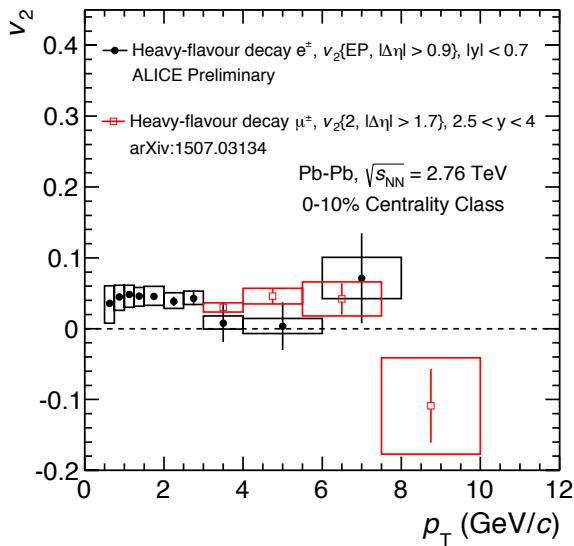


ALICE-PUB-70100



- **Positive v_2 measured**, hint of increase of v_2 going to more peripheral collisions
- Magnitude comparable to that of charged particles
- **Evidence that heavy quarks participate in the collective expansion of the system**

Heavy-flavour decay lepton ν_2



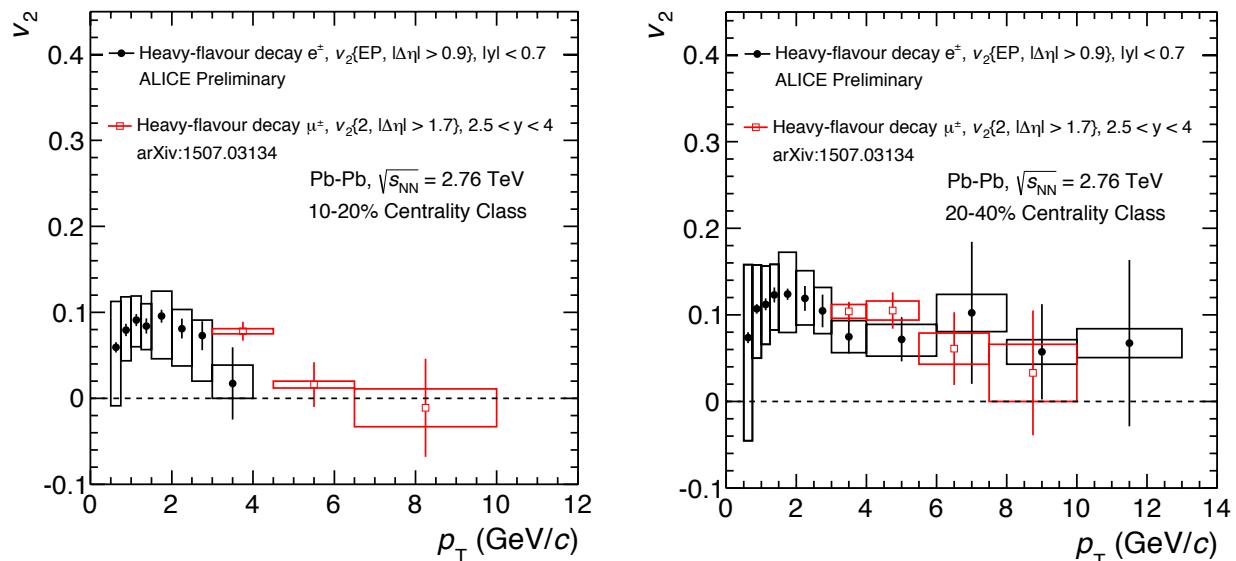
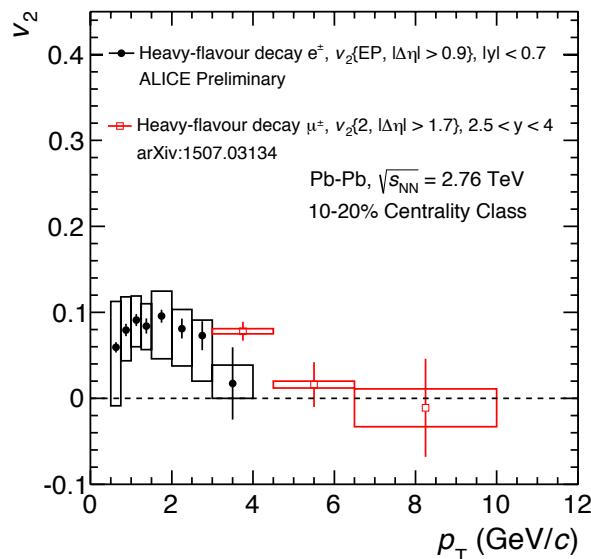
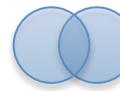
ALI-PREL-77612



ALI-PREL-77620



ALI-PREL-77628

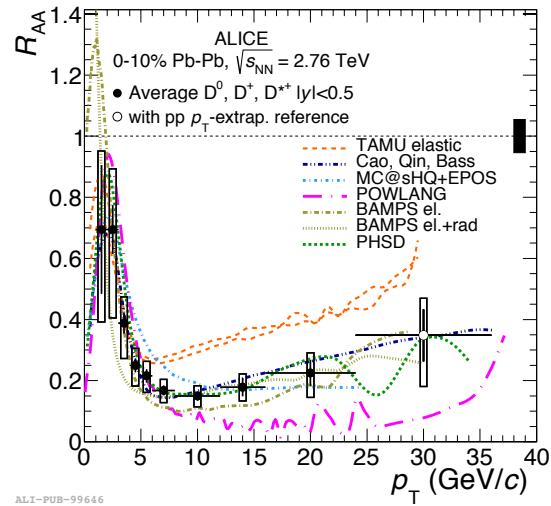
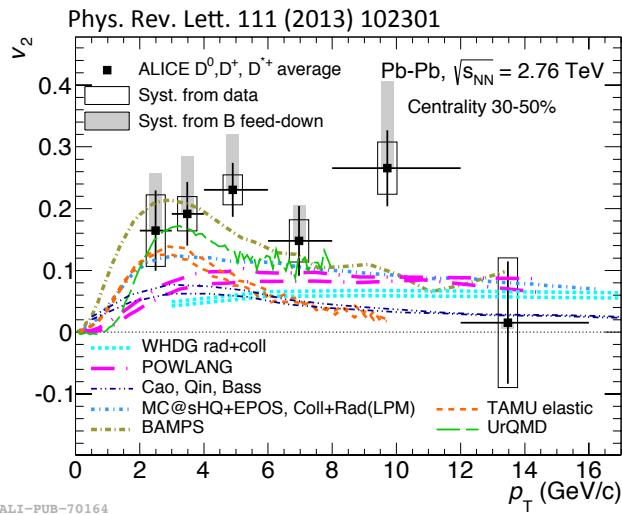


- **Positive ν_2 also measured using heavy-flavour decay electrons/muons**
- **Further evidence that heavy quarks participate in collective expansion**

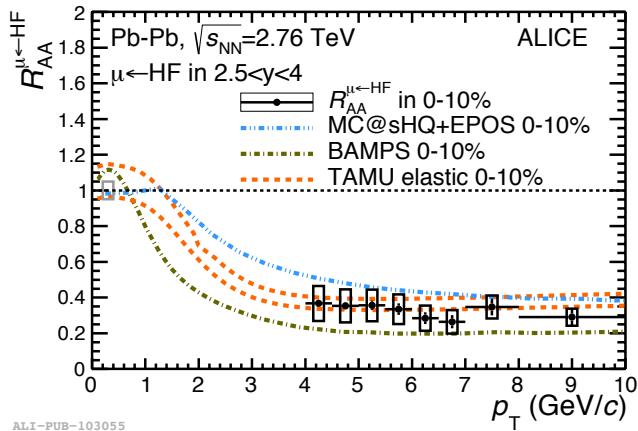
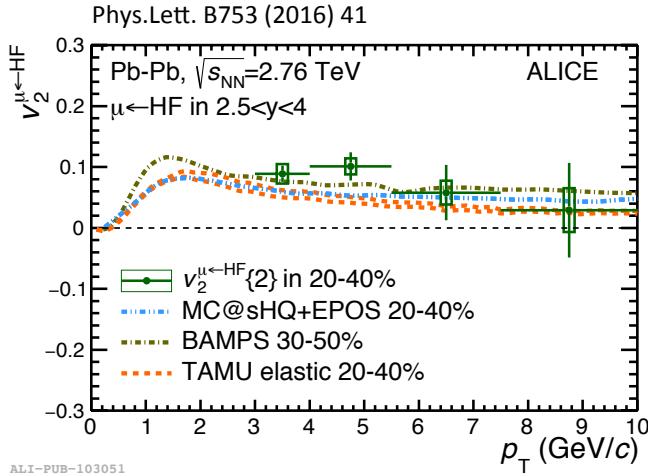


Model comparisons

D-meson



$\mu \leftarrow \text{HF}$



- Models begin to bring constraints on mechanisms contributing to R_{AA} and v_2

WHDG: Nucl. Phys. A 872 (2011) 256; TAMU: arXiv:1401.3817; MC@sHQ +EPOS: PRC 89 (2014) 014905;; POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph]; Cao,Quin, Bass: PRC 88 (2013);



Summary and Outlook

- **Lots of interesting results from LHC Run 1 data**
 - Multiplicity dependent yield of heavy-flavour particles measured to probe production mechanisms
 - p_T and centrality dependent production of heavy-flavour in p-Pb and Pb-Pb collisions explored over large p_T range
 - R_{pPb} and Q_{pPb} consistent with unity and models including cold matter effects
 - Large suppression in central Pb-Pb collisions consistent with collisional and radiative energy loss mechanisms
 - High p_T suppression consistent with mass-dependent energy loss for D/B mesons
 - Large positive elliptic flow measured for heavy-flavour particles
 - Heavy-flavour participation in collective expansion
 - R_{AA} and v_2 measurements can together begin to constrain models



Summary and Outlook

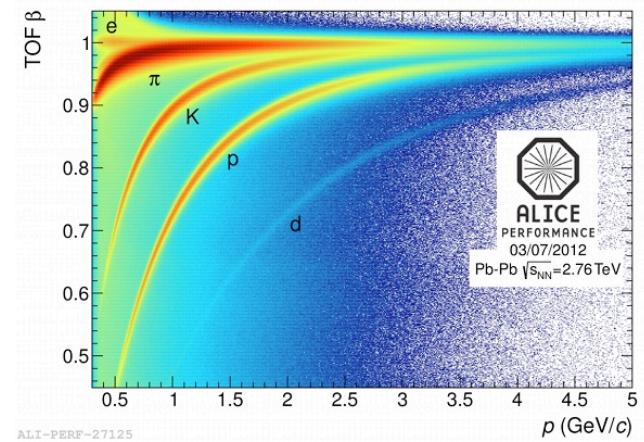
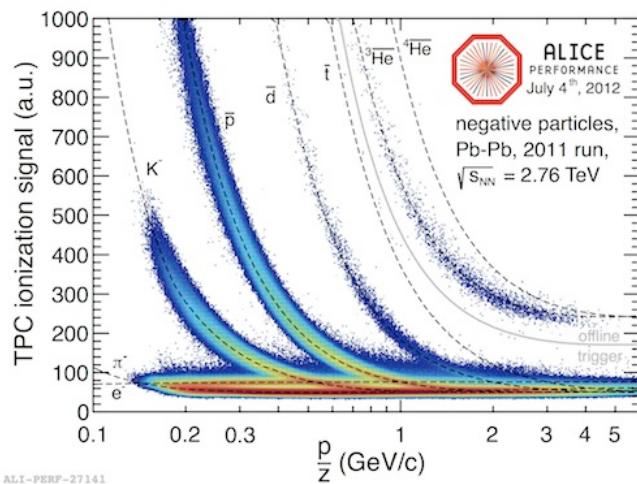
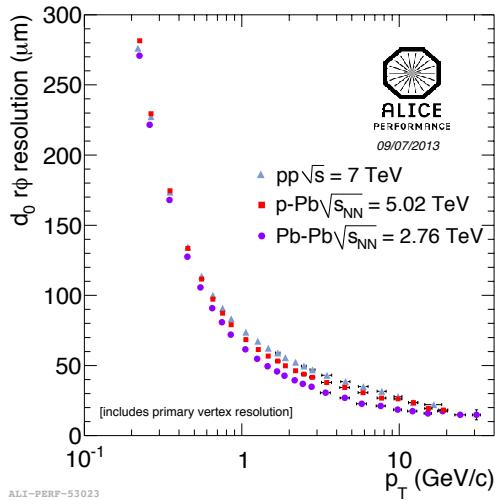
- **Lots of interesting results from LHC Run 1 data**
 - Multiplicity dependent yield of heavy-flavour particles measured to probe production mechanisms
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 - Large positive elliptic flow measured for heavy-flavour particles
 - Heavy-flavour participation in collective expansion
 - R_{AA} and v_2 measurements can together begin to constrain models
- **Many questions remain for Run 2 and beyond...**
 - Fresh data at $\sqrt{s}_{NN} = 5 \text{ TeV}$ – what happens in a longer lived, denser medium?
 - How does the production of heavy-flavour particles evolve in p-Pb/Pb-Pb at low p_T ?
 - Can precision measurement of charm and beauty be made at LHC?
 - Upgrade program for Run 3 (2021) includes full ITS upgrade, Muon Forward Tracker (MFT), continuous TPC readout for precision/statistical improvement
 - Further, more precise constraints to model calculations
 - B mesons, $\Lambda_c \dots$ will be directly accessible for first time in Pb-Pb collisions
 - **Plenty more to look forward to!**



Backup



Detector performance



Excellent vertex resolution, PID capabilities over a wide momentum range

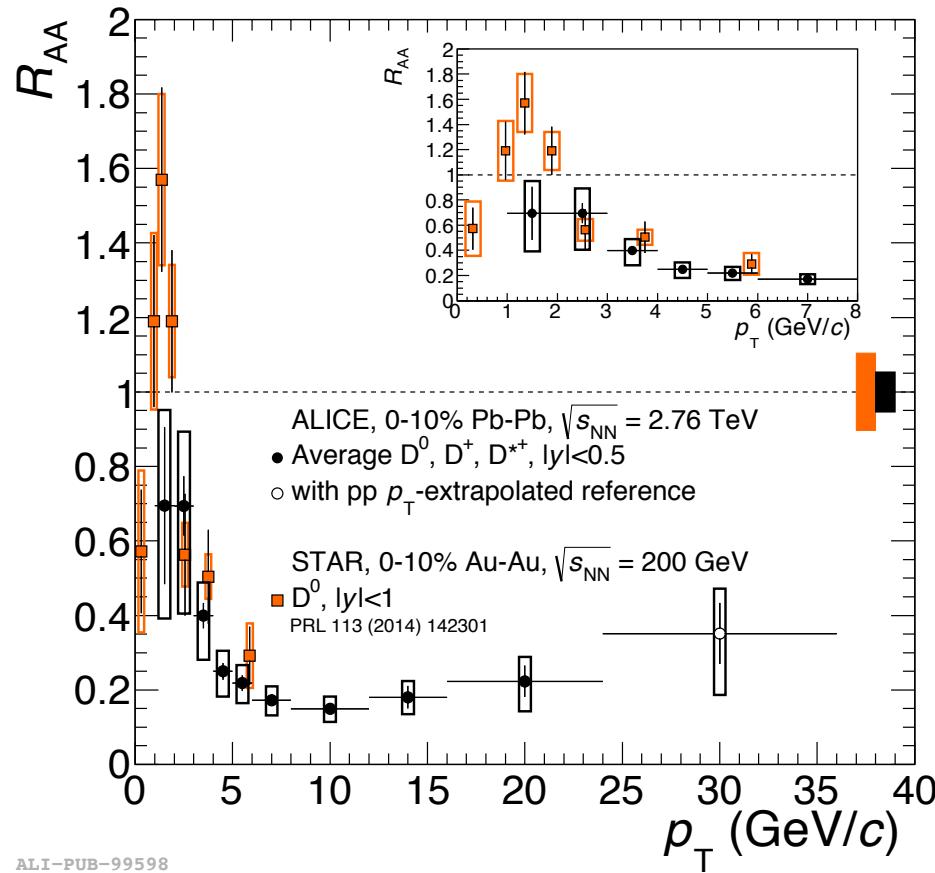


D-meson R_{AA} LHC/RHIC comparison



ALICE: arXiv:1509.06888

STAR: PRL 113 (2014) 142301



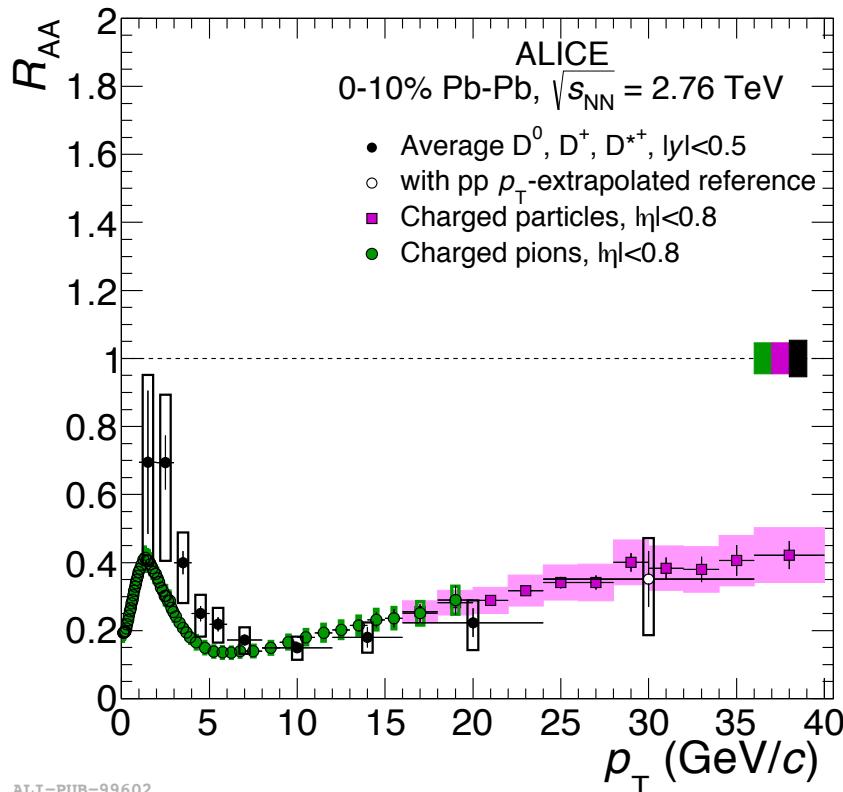
- Average D-meson consistent with D^0 STAR measurement
- Lower p_T reach needed to conclude on binary scaling of D meson production



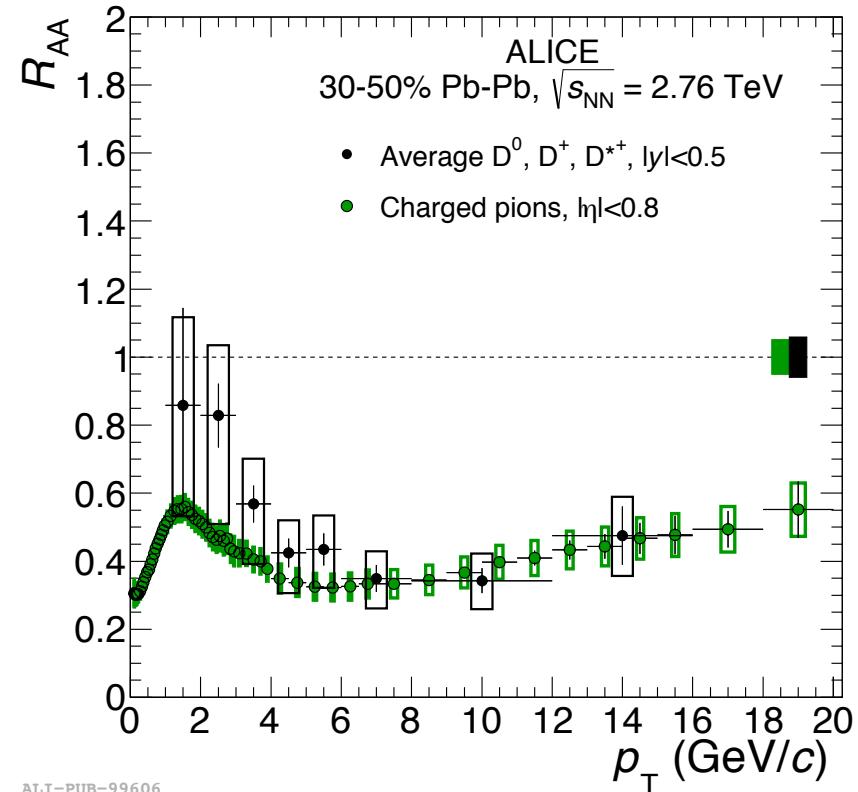
D-meson vs charged particles R_{AA}



arXiv:1509.06888

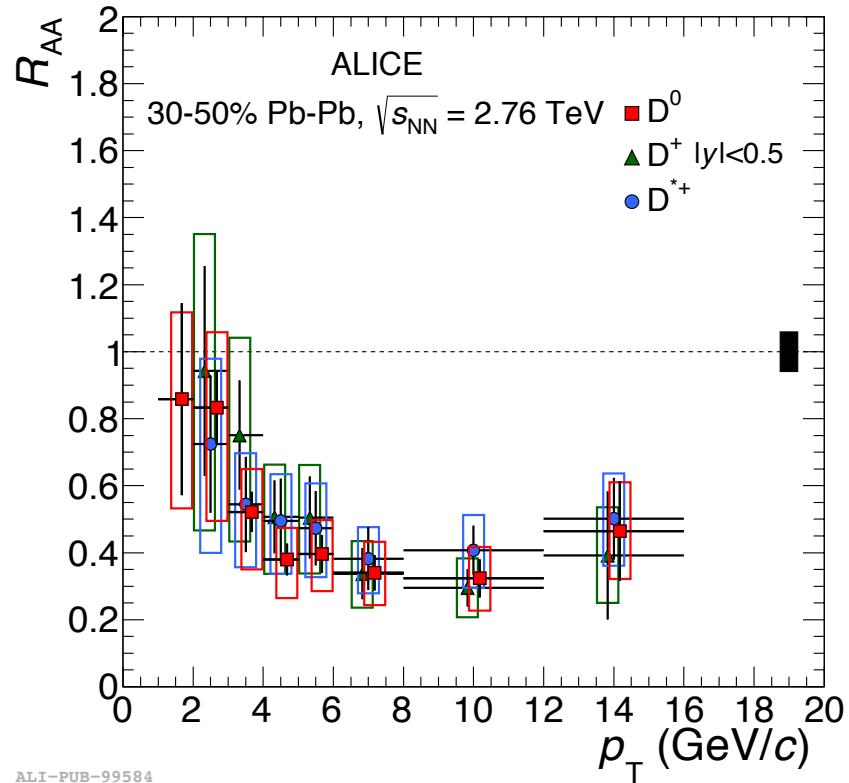
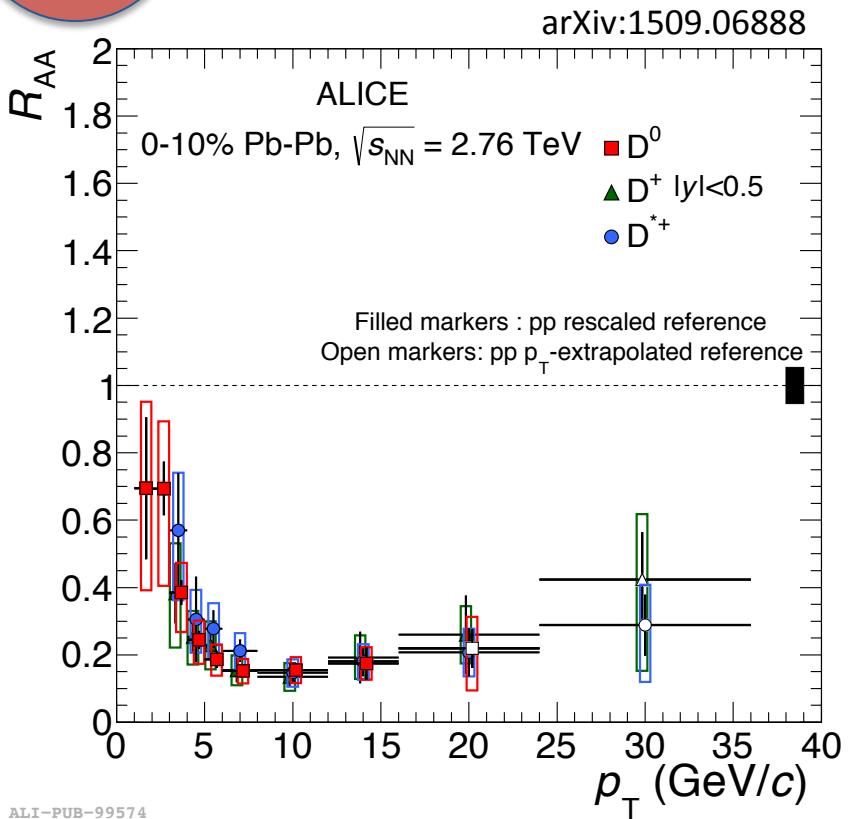


ALI-PUB-99602



ALI-PUB-99606

- R_{AA} vs p_T of D mesons consistent with that of charged particles within uncertainties

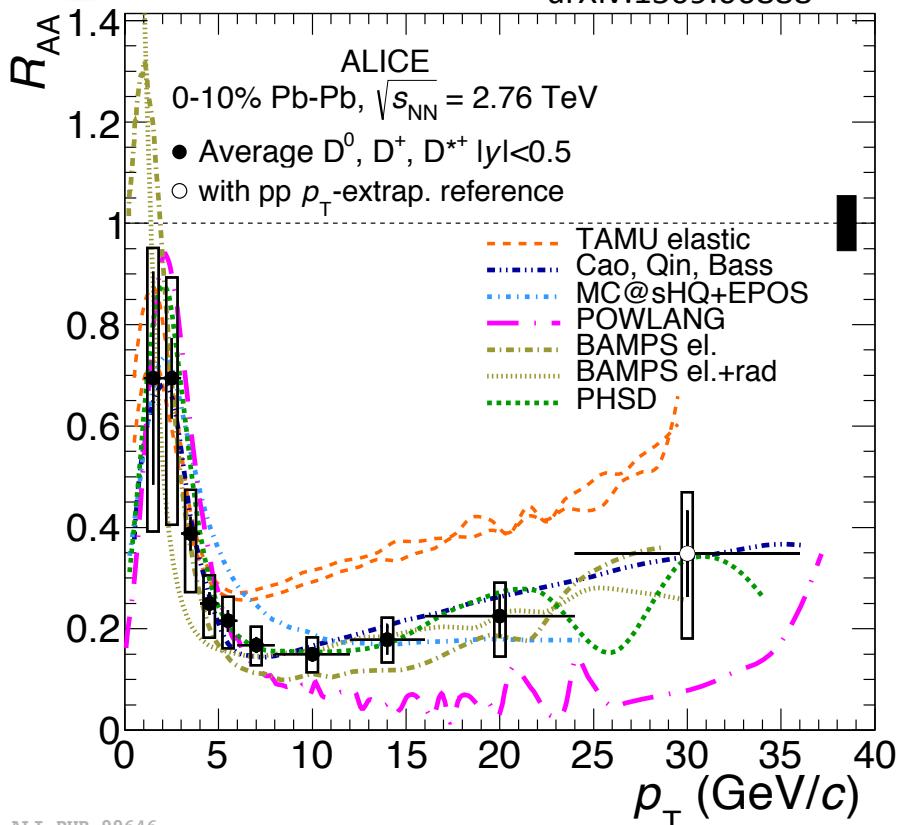
D-meson R_{AA} 

D-meson R_{AA} consistent over all measured D-meson species

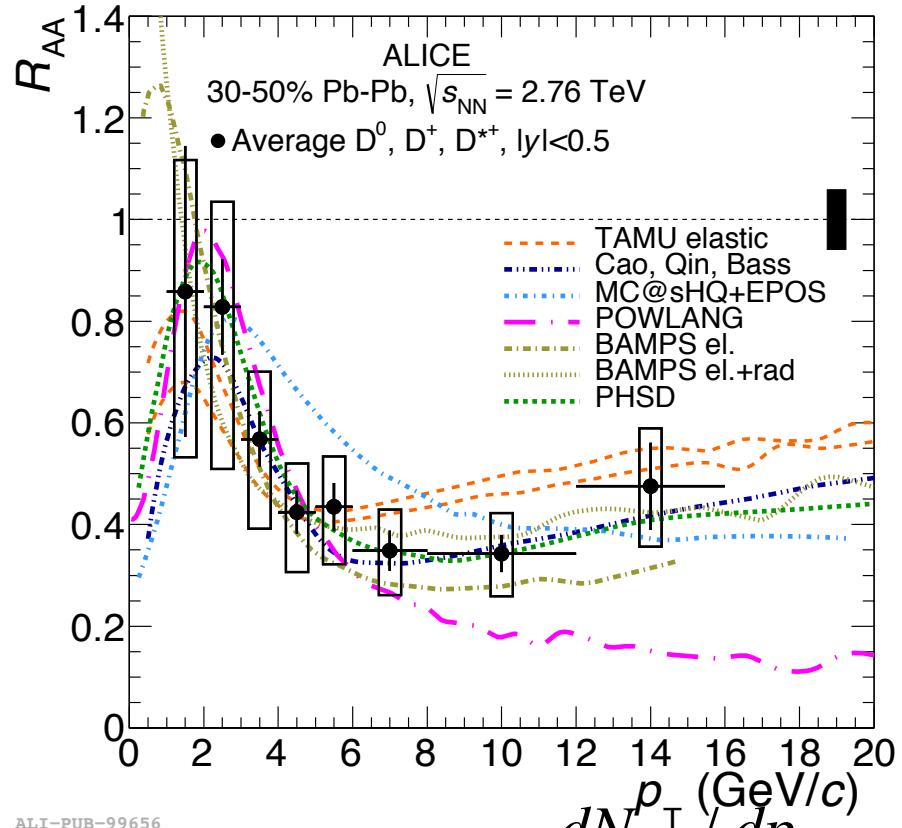
D-meson R_{AA}



arXiv:1509.06888



ALI-PUB-99646



ALI-PUB-99656

Strong suppression of D mesons seen in Pb-Pb:

- Described well by models which include collisional and radiative energy loss

$$R_{AA}(p_T) = \frac{dN_{AA}^T / dp_T}{\langle T_{AA} \rangle d\sigma_{pp} / dp_T}$$

TAMU: arXiv:1401.3817;; MC@sHQ +EPOS: PRC 89 (2014) 014905;; POWLANG: JPG 38 (2011) 124144; Eur. Phys.J. C71 (2011) 1666; BAMPS: PLB 717 (2012) 430;
 arXiv:1310.3597v1[hep-ph]; Cao,Quin, Bass: PRC 88 (2013);

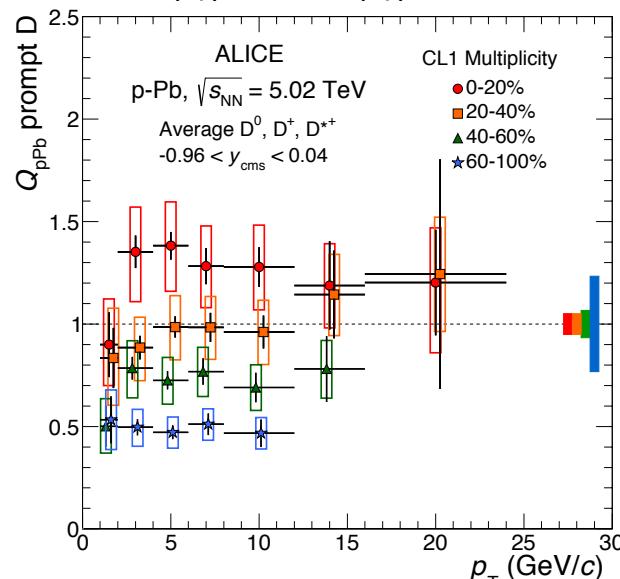


D-meson Q_{pPb}

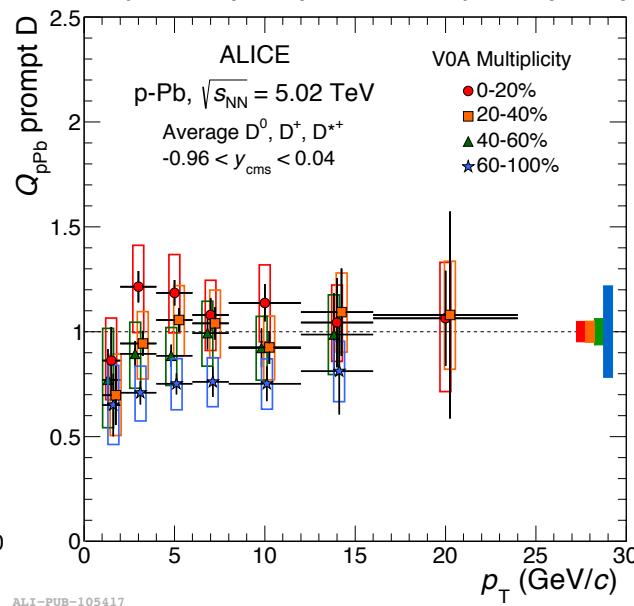
Increasing η -gap



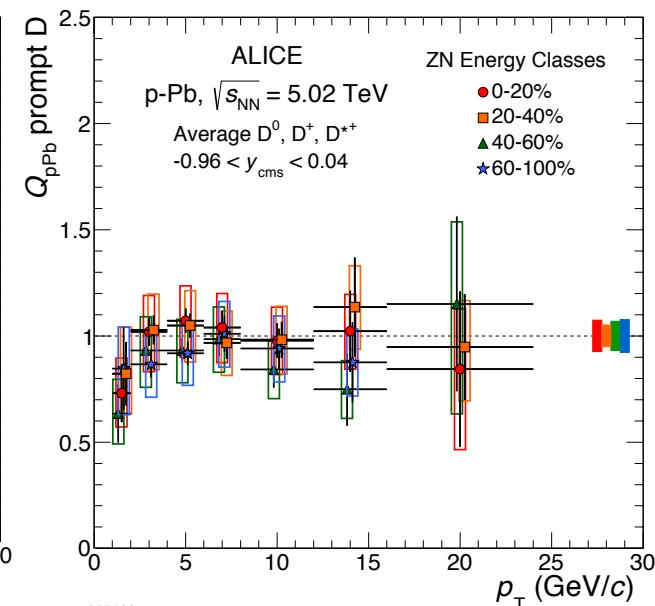
SPD: $|\eta| < 2.0$ and $|\eta| < 1.4$



-3.7 < η < -1.7 (VOC) and 2.8 < η < 5.1 (VOA)



ZDC

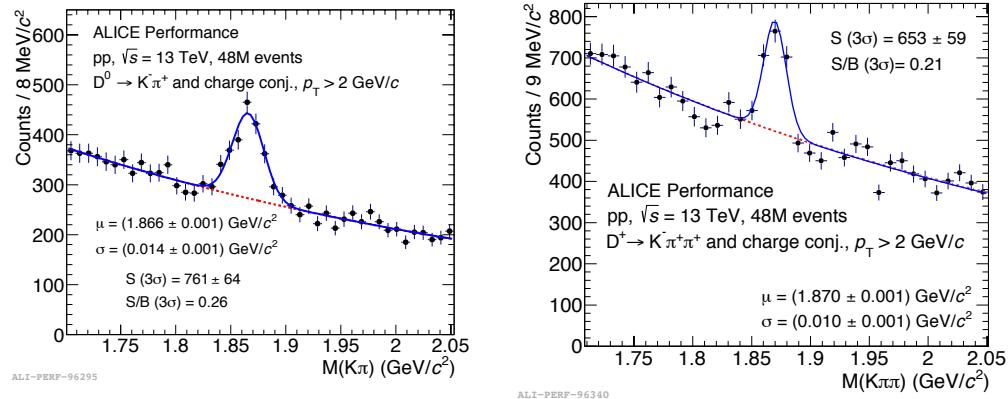




Future prospects (1)

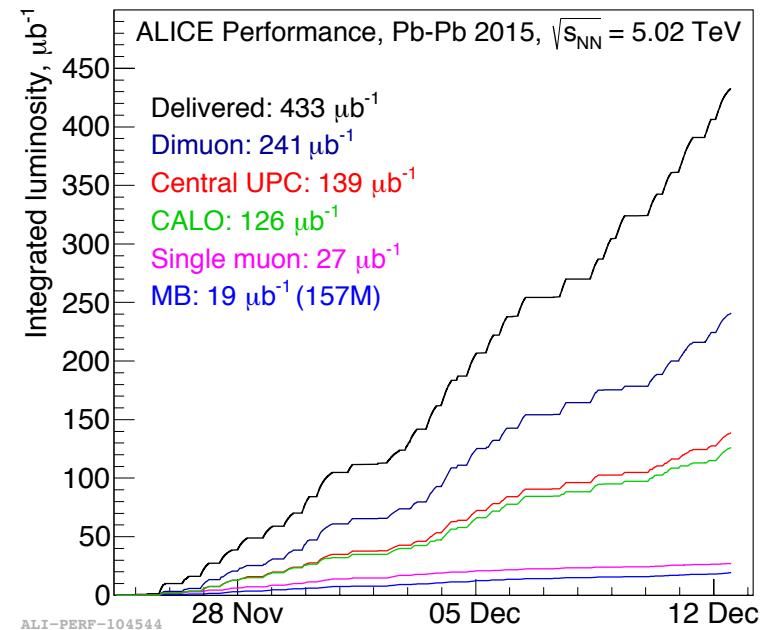
pp run @ 13 TeV

- LHC ran with pp beams from June–December
- Promising D meson peaks already seen with data from that period



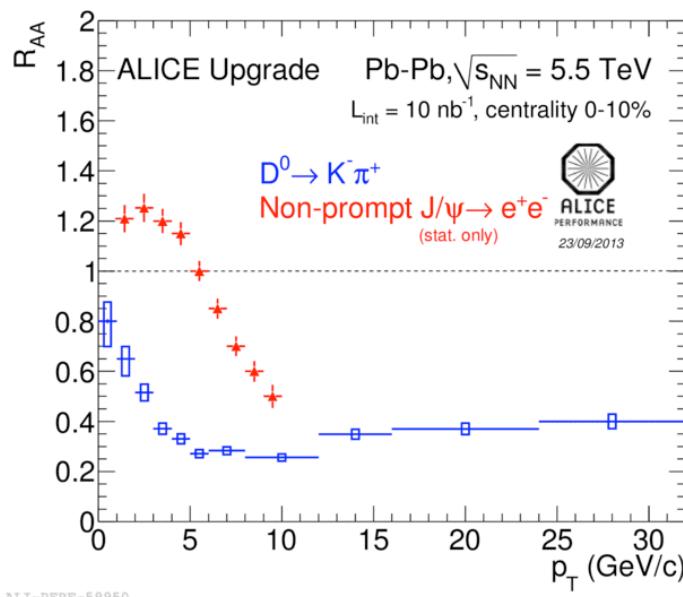
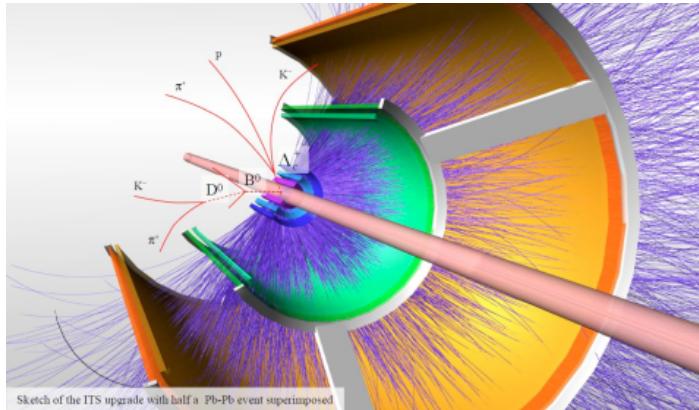
Pb-Pb run @ 5 TeV

- (Di)muon trigger and minimum-bias data taken in December 2015



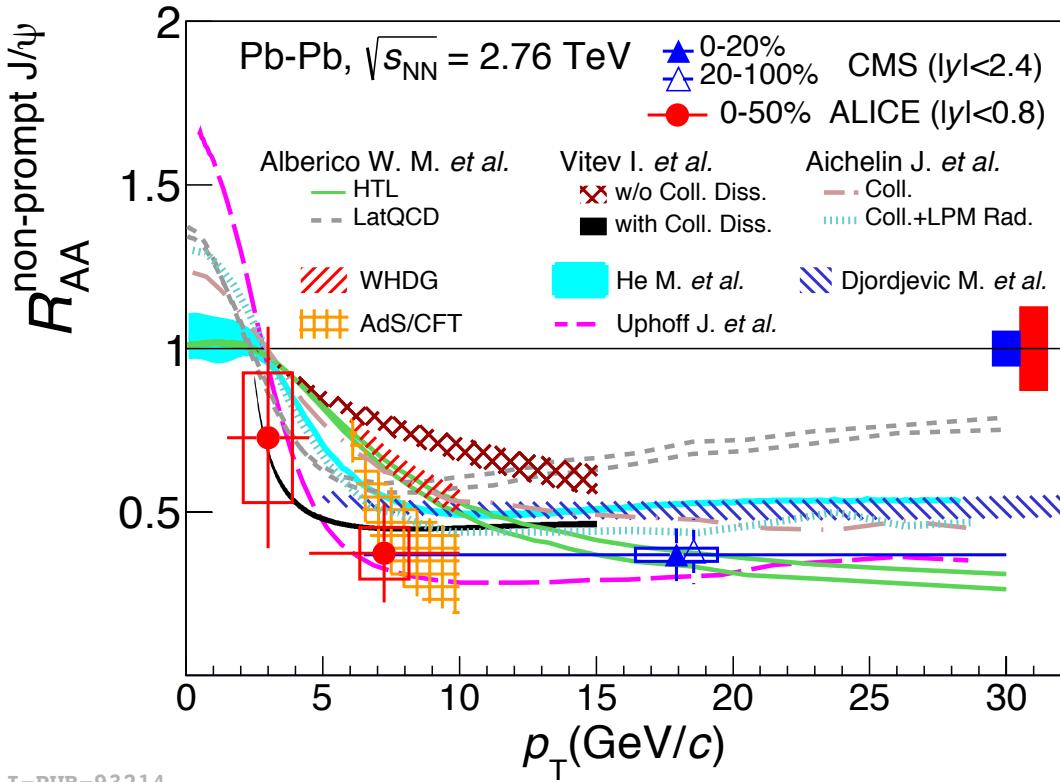


Future prospects (2)

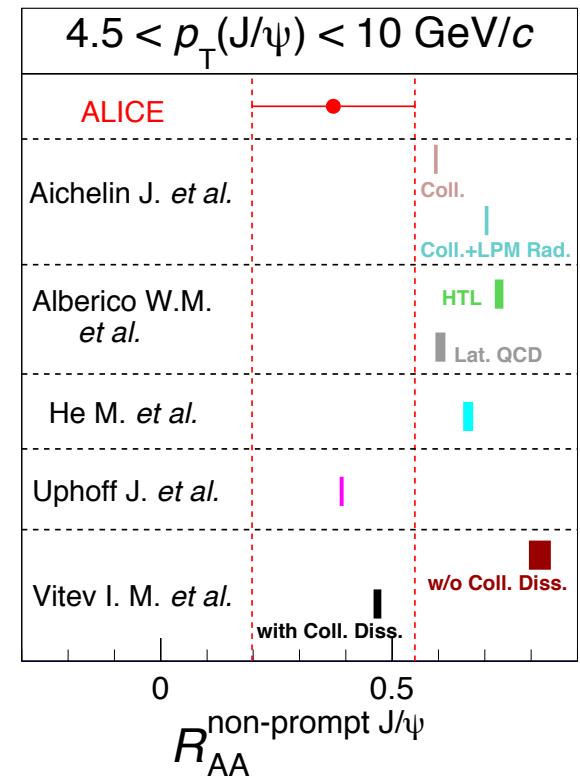


- **Inner tracking system undergoing major upgrade** for Run 3 (~2020)
- **7 layer silicon pixel detector** will feature:
 - **Reduced beam pipe** 29 → 17.2 mm
 - **Reduced material budget** 350 → 50 μm
 - → **Improve impact parameter resolution** by a factor of ~3 in (r-φ) and ~5 in (z)
 - **Improved readout rate** 1kHz → 100 kHz
- Will allow for many precision measurements
 - D, B mesons, Λ_c , Λ_b , charmonium/bottomonium...

Non-prompt J/ ψ R_{AA}



ALI-PUB-93214

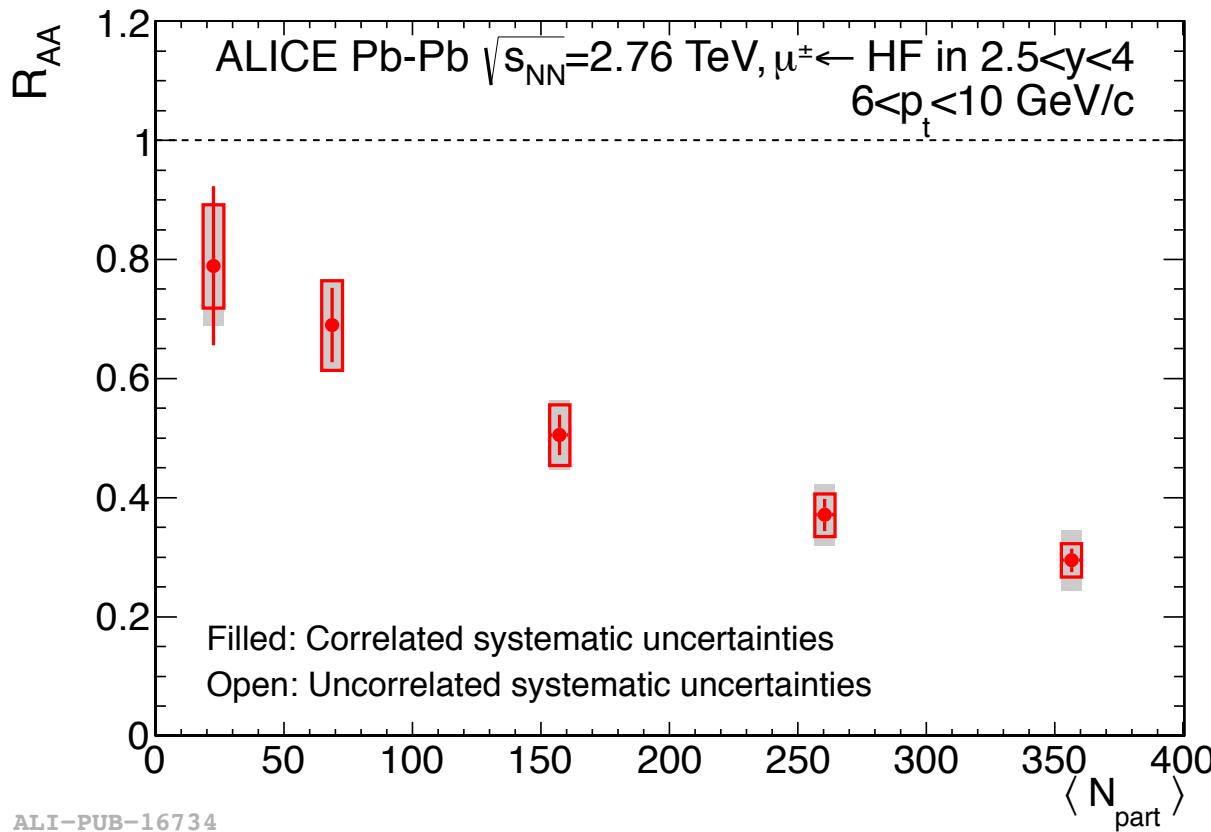


ALI-PUB-93218

- Suppression of non-prompt J/ ψ also seen by ALICE in 0-50% centrality



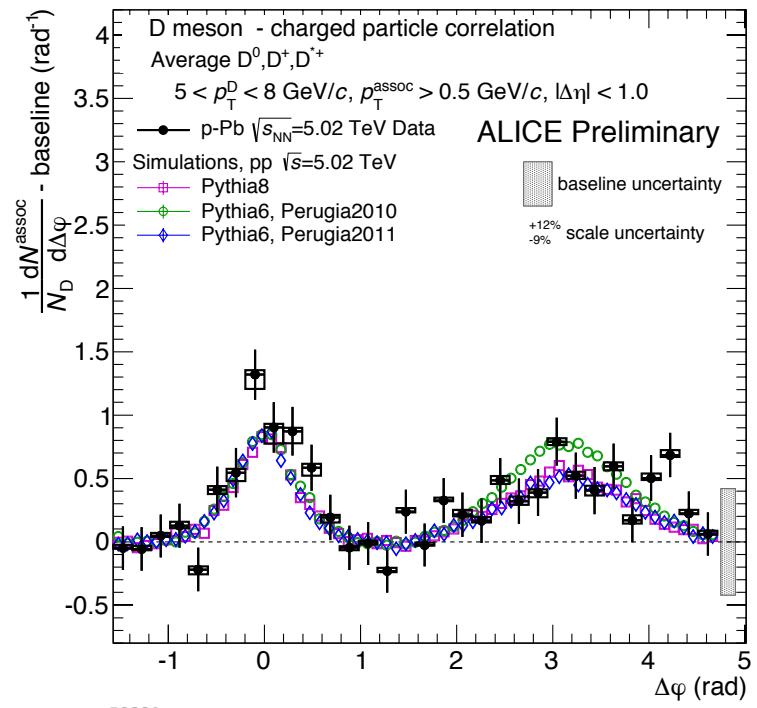
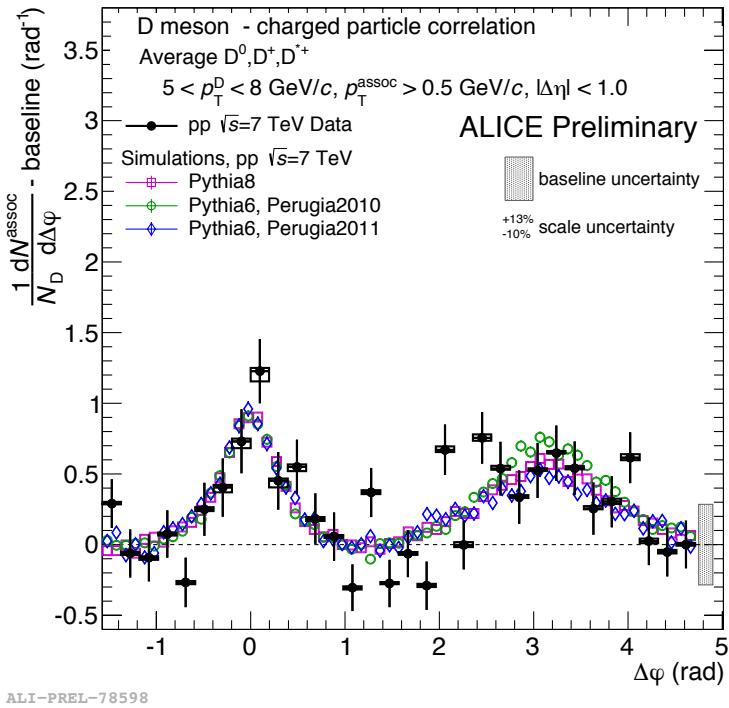
HFM Pb-Pb



Heavy flavour muon suppression increases for more central collisions



D-h correlations



- Study quark production, fragmentation, and possible modifications of angular correlations
- $(\Delta\phi, \Delta\eta)$ correlation of the heavy-flavour candidate (“trigger”) with the other charged tracks in the event (“associated particles”)
- Good agreement with PYTHIA